Indoor agriculture

Can it make significant contributions to food security under climate change?

Bruce M Campbell

Key highlights

- Indoor agriculture–greenhouse production, controlled environment agriculture, vertical farming has many positive features, and is undoubtably part of a transformed food system. However, there are some important challenges that need to be addressed.
- The greatest asset of indoor agriculture is its ability to reduce the need for land and inputs, through harnessing precision agriculture.
- The impacts of indoor agriculture on food waste and taste cannot be generalised.
- Health of agricultural workers can be compromised by greenhouse production, through pesticide spraying.
- From a climate perspective, the high energy demands of indoor agriculture if based on fossil fuel is a major problem.
- Localising production is not good enough if fossil fuels are used in indoor agriculture, with many cases showing that the carbon footprint of distantly located open fields will be lower than that of indoor agriculture.
- Indoor agriculture based on renewable energy is the future, but renewable energy comes with significant capital costs.
- The diversity of crops grown through indoor agriculture must increase if indoor agriculture is to contribute to broader food security agendas.
- While there are several challenges, policy support and technical advances will see indoor agriculture advancing to be a key feature of transformed food systems.

Indoor agriculture has many positive features, but....

Indoor agriculture–greenhouse production, vertical agriculture, controlled environment agriculture–offers a means to provide optimal conditions for plant growth as compared to open field production. Indoor agriculture is viewed as a key element of a transformed food systems, and can help society deal with increasing climate extremes, less predictable and variable rainfall, and unfavourable temperatures. However, challenges remain. Traditional open field agriculture has multiple negative impacts on the environment, some of which indoor agriculture can mitigate. In general, indoor agriculture reduces the need for land, increases the efficiency of water and fertiliser use, and reduces the need for pesticides.[1,2]

But for any generalisation, there are important exceptions, given the many types of open field production and the diverse forms of indoor agriculture production. To illustrate some exceptions, agrochemical use in Chinese greenhouses was found to be excessive, in terms of pesticides[3] and fertilisers[4] even in comparison to open field production. Soils in greenhouses showed significant soil acidification and salinization. There are also issues related to wastage, taste and the health of agricultural workers that need to be considered. But the most problematic issue for indoor agriculture relates to energy usage and GHG emissions. Without moving to renewable energy, indoor agriculture has no role in a future transformed food system.

We firmly believe that indoor agriculture will increase in prominence in the food system and that it is a crucial component of a transformed food system. Thus, while we point to the challenges that it faces in some of the subsequent sections, this is meant to stimulate innovative institutional and technical solutions, not to dampen enthusiasm.

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Precision agriculture in indoor agriculture is reducing inputs

Indoor agriculture offers the opportunity for greater control of plant growing conditions, more reuse of water and better management of plant pests and diseases with resultant lower needs for pesticides–in short, precision agriculture is more easily applied. For instance, field-produced tomatoes generally use more pesticides for production as compared with greenhouse-produced tomatoes, and thus field-produced tomatoes are reported to be less preferred by health-conscious consumers.[5]

For vertical farms, water may leave only as part of the harvested product, which would reduce water use by circa 90% compared with greenhouses and by circa 99% compared with open fields.[6] In very intensive greenhouse soilless production systems with recirculating nutrient solution, as is commonly used in the Netherlands and Belgium, tomato yields are approximately seven times those of outdoor tomato production in Southern Europe while about 10 times more fruit can be produced per unit of water.[7] Significant irrigation water savings can be made through greenhouse production compared to open field cultivation in arid climates such as Egypt.[8,9]

It is also possible that water use along the value chain can be reduced through indoor agriculture: e.g. lettuce produced from pesticide-sprayed open fields will need considerable washing, whereas lettuce produced indoors with no pesticides and potentially through soilless methods will not need to be washed. Indoor agriculture limits the amount of land needed for food production, and thus does not have the negative impacts that open field production can have, e.g. increasing deforestation and reducing soil health.

Indoor agriculture has unclear impacts on food waste

Local production with indoor agriculture reduces the period between harvest and purchase. This could reduce food waste by minimizing transport and storage spoilage, and lengthen shelf life, helping reduce household waste.[10] The shelf life of open field–produced tomatoes was reported to be shorter because fruits require washing to remove soil and dust particles before marketing.[11] For every generalisation

there is the exception, so for strawberries shelf life was found to be longer for open field production compared to greenhouse production.[12] In a global review of studies, no differences in the amount of wastage generated could be distinguished between different production systems (open field vs. greenhouse) for tomatoes, mainly as an effect of the small amount of studies considering food waste.[13]

Taste can be impacted by the production system

Taste of products–and quality more generally–between open fields and indoor agriculture shows no consistent pattern, being highly dependent on varieties being compared and production conditions. In one study in Oklahoma, tomatoes produced under open field conditions were rated significantly greater for taste compared with those produced under greenhouse conditions.[14] In Trinidad, open field lettuce displayed diverse taste profiles while greenhouse lettuce leant towards bitterness.[15]

Greenhouses yielded firmer textures. In Iran, open-field production of strawberries yielded higher values for fruit quality indices (firmness, taste).[16] But results are highly context (and variety) specific: Latvian work on strawberries showed the same pattern for firmness but other sensory parameters were not significantly different among production systems.[17] Open field agriculture has decades of breeding work to build on; we need stepped up breeding programs targeted to indoor agriculture, where taste (and other characteristics) get appropriate attention.

Health of agricultural workers can be compromised by greenhouse production

The health of agricultural workers can be negatively impacted by greenhouse production–especially related to pesticide spraying, which is compounded by high temperatures, high humidity and possibly poor ventilation systems. Poor ventilation can increase the accumulation of pesticide levels, thereby causing toxicity effects even at lower concentrations.[18]

Most commonly reported health effects, which include respiratory, pulmonary, reproductive, hormonal, neurological, and skin problems, were attributed both to short- and long-term exposure to pesticides.

From a climate perspective, energy use based on fossil fuel is a major problem for indoor agriculture

The Achilles heel of indoor agriculture production comes through high energy usage. If this is based on fossil fuels, then indoor agriculture has limited role to play in a food system that must transform under climate change. Some will argue that in certain parts of the world water may be a major problem and thus in those areas, indoor agriculture, even if based on fossil fuels, would be appropriate.

Heating, cooling, carbon dioxide enrichment and lighting need much more energy than the energy needed for open field production.[19] This drives up GHG emissions, but is also a major component of costs. Energy is usually the second largest overhead cost in greenhouse crop production, after labour costs.[20] Reducing high energy demand based on fossil fuel can be regarded as the key industry sustainable development goal. In northern latitudes and extreme climates, the cost of heating and cooling greenhouses can reach 70–85% of the total operating cost. In Northern climates up to 90% of the annual greenhouse energy demand comes from the need for heating in winter months.[21]

Greenhouse tomato produce.

Empirical data for lettuce cultivation in the Netherlands showed that the carbon footprint of vertical agriculture was 16.7 times greater than that of open fields and 5-7 times greater than greenhouses.[22] In Washington State (USA), high-tech greenhouses in comparison to open-field production gave 6.4 times yield per unit area but with 231 times energy and 18 times GHG footprints per unit of fresh tomato mass.[23] Only water footprints were positive, greenhouse footprints being 0.74 times those of open fields. In China, GHG emissions from greenhouse vegetable production were 55.4–84.1 % greater than those from open-field vegetable production, [24] because of greater use of fertiliser in the greenhouses, so energy use is not necessarily the primary driver of GHG emissions in all contexts.

Localising production is not good enough if fossil fuels are used

Local production through indoor agriculture can shorten supply chains and thus reduce transport costs and transport-related GHG emissions. However, this may not be too significant in relation to GHG emissions, given that transport has quite a low contribution to the total carbon footprint of most products (<10%) and entire diets (6%).[25] So for example, a life cycle assessment showed that lettuces grown in a local greenhouse in St Louis contribute to more GHG emissions than lettuces grown in open fields and flown in from California.[26] GHG emissions from the heating of high-tech greenhouses in northern countries are higher than vegetables produced in southern Europe in unheated tunnels and transported to northern countries.[27]

Indoor agriculture based on renewable energy is the future

The situations referred to above, where energy intensive greenhouse production has a larger carbon footprint than production from distantly located open fields or unheated tunnels, can be turned around if renewable energy is used. In the St Louis vs California comparison, the carbon footprints of greenhouse production in St Louis would have been lower than the open field sourced production in California, if renewable energy was used in St Louis.[28] In a section above, we reported that the carbon footprint of vertical agriculture for lettuce in the Netherlands was 16.7 times greater than that of open fields and 5-7 times greater than greenhouses, but if renewable energy was used and avoided deforestation was included, these numbers would be reduced from 16.7 times to 3.3 times, and from 5-7 times to 2.3-2.4 times.[29] If a UK vertical farm for lettuce used renewable energy then it would have a lower carbon footprint than imported lettuce from open fields in Spain.[30] The global warming potential of tomato production in heated greenhouses can vary by

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50 fold, indicating the potential for energy and emissions efficiency, with the larger values corresponding to cases where natural gas or oil is used for heating and electricity.[31]

But renewable energy comes with significant capital costs

Energy source is obviously extremely important. If indoor agriculture production is to have any place in a world dogged by climate change, then the source of energy must be renewable. The actual environmental sustainability of indoor agriculture will depend greatly on local methods of energy production.[32]

But shifting to renewable energy can also raise costs, and so breakthroughs in indoor agriculture production are predicated on breakthroughs in the energy sector – for energy production and energy storage. Energy storage is crucial to secure stability in energy supply. The usage of thermal energy storage systems can increase the thermal performance of solar greenhouses by 29%.[33]

The main strategies applied in greenhouses to increase energy-saving include: (i) energy-efficient structural design, (ii) installation of energy-efficient screens, (iii) installation of energy-efficient heating, ventilation, and lighting systems, and (iv) installation of energy-efficient environmental control systems.[34] Energy storage systems include underground thermal energy storage and water tanks.

Indoor agriculture produce.

Capital costs for greenhouse production are high. In South Korea, the operation of solar heat and heat pump systems reduced GHG emissions by 53.4–73.1% and reduced operating costs by 81.9–82.8% compared to conventional oil and electric boilers, but due to the high initial capital costs, the payback period was circa 25 years.[35] Similarly lengthy payback periods are recorded for Europe.[36]

The diversity of crops grown must increase

Given the high costs, current indoor agriculture is limited to a narrow range of products that achieve relatively high prices in urban areas – tomatoes, lettuce and other such vegetables.

For these vegetables, R&D is most advanced. For example, in a review of growing crops in vertically stacked hydroponic beds under sole LED lighting in a controlled environment—including vertical farms or plant factories, of the 610 articles found, the majority covered leafy vegetables,[37] Vegetables are nutritionally important, but current indoor agriculture production of a limited set of vegetables, means that indoor agriculture production contributes minimally to the broader food security agenda and cannot yet claim to be a large part of the food transformation agenda. Considerable attention in innovation systems needs to be given to a broader set of crops.

Indoor agriculture can be advanced through attention to the problems

The following needs attention if indoor agriculture is to be a significant component of a transformed food system:

- Most mportantly, use of renewable energy
- Attention to the health of agricultural workers
- Reduced use of pesticides
- More precision agriculture in terms of fertiliser use
- Greater degrees of circularity in relation to water and minerals
- Increasing crop types and attention to taste, backed up scaled up breeding programs targeting indoor agriculture

Major advances for indoor agriculture are likely to come through: breakthroughs in the energy sector in terms of the costs of renewable energy production and storage; smart structures; greater levels of automation through

sensors, IoT and AI; and crop breeding efforts directed more to indoor agriculture production (e.g. focussing more on taste and less on yield). As an example, AI systems have out-performed human-operated systems in an experimental situation in the Netherlands.[38]

To achieve advances governments can provide incentives to greenhouse production, such as subsidies, carbon credits and supporting more R&D. For example, shifting from fossil fuels to renewable energy for greenhouse production in South Korea would advance national energy independence and contribute to national efforts to reduce carbon emissions. If government introduced carbon trading and those shifting would get carbon credits for their GHG reductions, then the payback period for shifting to renewable energy would decrease from 25 to 14 years.[39]

Local and urban governments can also stimulate advances. For example, "Circular City Greenhouses", which combine high-tech greenhouses and repurposed urban waste streams,[40] need the support of city governments and their planning departments.

Open field breeding programs have given considerable attention to pests and diseases, and increasing yield. Given that pest and disease attack may be easier to deal with in controlled environment agriculture and given yields are already considerable in indoor agriculture, it is feasible that breeding for indoor agriculture can be more focussed on nutrition and taste, to the benefit of consumers. There are many options for advances to be made. We need to stimulate these to advance production from indoor agriculture.

Greenhouse agriculture production.

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Suggested citation

Campbell B (2024). Indoor agriculture – can it make significant contributions to food security under climate change? Discussion Starter: 8. Wageningen, the Netherlands: Clim-Eat.

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