INDOOR SOILLESS FARMING:

PHASE I: Examining the industry and impacts of controlled environment agriculture

WWF

ACKNOWLEDGMENTS

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EXECUTIVE SUMMARY

Soilless vertical and indoor urban farming is a growing niche industry that aims to reduce many of the environmental impacts of conventional agriculture. At scale, this method of farming could decrease pressures on land, biodiversity, natural habitat, and climate. However, the industry also faces hurdles that prevent it from moving beyond its current specialization. The Markets Institute at WWF is working on an Innovation Analysis of Indoor Soilless Farming. In Phase 1, we began exploring the possibility of boosting the domestic - and eventually global - indoor soilless farming industry by leveraging stranded assets and building a robust coalition of local partners to launch a pilot farming system. Phase I activities included:

- conducting a life cycle analysis (LCA) of controlled environment systems;
- analyzing the future of indoor and vertical farming;
- determining the optimal conditions of farms; and
- convening a St. Louis-specific research and stakeholder working group.

We found that the controlled environment agriculture (CEA) industry continues to face significant hurdles, especially around energy and labor, but that it also offers unique opportunities around local food, safe food, and supply chain resilience. This is a young industry with technologies that continue to improve, driving down the cost and opening up new possibilities. We believe that St. Louis could offer unique advantages for a CEA system, including stranded assets and unique partnerships. We look forward to exploring those with the Stakeholder Working Group as we kick off Phase II.

Currently, lettuce grown in a greenhouse or vertical farm remains more expensive than conventionally grown lettuce produced in California and shipped to St. Louis, even though the costs of the former have dropped significantly over the past decade. The costs of CEA are largely due to labor and energy use. CEA farming also has a large environmental footprint for some key metrics. There were three main impact areas that the Markets Institute at WWF identified as important in our Life Cycle Analysis: contribution to climate change, land use, and water use. Conventional agriculture has a lower climate change impact than CEA, primarily because of its lower electricity footprint and the cleaner mix of electricity sources in California. And, land was cleared likely long ago where most successful conventional agriculture is taking place. However, CEA excels in other areas: greenhouse hydroponic agriculture receives the best scores for land use and water use, with vertical hydroponics coming in second, followed by conventional agriculture. It is important to note that this does not include an analysis of larger indirect environmental consequences caused by conventional agriculture, such as damage caused by dams, air and water pollution from the field, and other factors.

The indoor, soilless farming industry is attracting attention and money, growing quickly, and bringing key benefits. However, it remains a nascent, disparate industry with several risks that must be addressed before it can achieve scale. There are many innovations under development that could affect WWF's analysis, including progress in lighting, fiber optics, AI and machine learning, gene editing, renewable energy, co-location and co-generation, and waste and recycling. While some of these innovations may not come to fruition, many have the potential to significantly change the cost and environmental footprint to drastically alter the mid- to long-term viability of the CEA industry. For example, hydroponic farms could achieve lower environmental impacts than conventional agriculture by sourcing their electricity from renewable energy like solar or wind, which is increasingly available in Missouri, instead of the standard regional mix currently used in St. Louis. Right now, it is not cost-effective nor necessarily a good use of resources to cover enough land with solar panels to run an entire farm, but that calculus could change in the next few years—or sooner, if other efficiencies come into play.

There are other key reasons that this industry is attracting excitement and capital. Consumers are becoming increasingly discerning about their food, demanding fresh, local, and organic produce all year-round. Companies are interested in securing supply chains that might otherwise be at risk due to the impacts of weather variability and climate change. And, food safety is becoming more of a concern. In the CDC's recent warning against consuming lettuce from Salinas, California due to possible E. coli contamination, the agency specifically noted that this warning did not extend to lettuce grown indoors, in greenhouses or hydroponically. The ability of individual, tightly controlled farms to ensure food safety could be a key differentiator for the industry.

Consumers and businesses are showing a growing interest in CEA food, and the technology to help the industry satisfy that demand is evolving very quickly. We need to monitor those changes. But, beyond technological issues, innovations, and natural market shifts, we must consider a range of other possibilities that could affect the efficacy of these systems. CEA systems of local production might become even more attractive if climate change affects California production and other regions more quickly than expected; if renewable energy becomes the norm; if communities value local food production, the elimination of food deserts, and job creation; or if new business models favor values different than those emphasized in current production systems.

The accompanying report aims to provide the best data available at this point in time and to identify what innovations and trends need to be monitored to reduce current costs and risks. WWF will share the report with the Stakeholder Working Group to kick off our discussions and serve as a resource to inform group decisions on what system seems best in the short term, where it could be located, which partners are needed, and more. The analysis focuses on the environmental costs and benefits more than financial costs and potential profits, largely because little cost information is available and WWF views this project through an environmental lens. However, we recognize that costs may drive more of the decisions as we move forward with a pilot design.

In 2020, we will kick off a Stakeholder Working Group and, ideally, begin the design of a pilot that will serve as a test case to see if there is a financially feasible way to scale the industry. We have identified several systems and partnerships that are worth exploring in St. Louis and believe that one of them will be chosen as a viable concept so we can move forward with a dynamic roadmap and a credible business plan. It is also possible that the system chosen could be the first step in a modular approach that shifts as we learn more and continue to find ways to drive costs down. By working as a group to make those decisions, when this project ends, key players will already be invested and ready to move ahead with building a pilot system that can be replicated worldwide, making food production more environmentally sustainable.

BACKGROUND

Food production is the largest human impact on the planet. Habitat conversion, greenhouse gas (GHG) emissions, soil degradation, agrochemical runoff, and inefficient water use associated with current food production systems threaten the environment. WWF envisions a food system that meets the needs of both people and nature, but to get there we must decrease the environmental impacts of food production through more efficient use of inputs, decreasing waste, reducing associated GHGs, and examining how to sustainably produce more food closer to consumer.

Soilless vertical and indoor urban farming is generating excitement as a growing niche industry that aims to reduce many of the more harmful effects of traditional farming. At scale, this method of farming could decrease pressures on land, biodiversity, natural habitat, and climate. However, the industry also faces hurdles that prevent it from moving beyond its current specialization in high-end leafy greens. Farms face difficulties related to energy and labor and need support to share experiences and move the industry forward.

The Markets Institute at WWF identified this as a trend worth investigating for the industry's potential to decrease the environmental impacts of our current food system, if it were able to overcome its hurdles. During Phase I of its Indoor Soilless Farming project, the Markets Institute research team began laying the groundwork to boost the urban soilless farming industry by:

1) Examining the potential to leverage stranded assets. These include large infrastructure investments such as power plants, postal hubs, or even caves previously used for industry, that have depreciated in value but will continue to function and be used in at least a limited capacity for 10-50 years, and the byproducts of such industries including brownfields; and

2) Building a robust coalition of local partners that can launch a pilot farming system

This groundwork also included conducting a life cycle analysis (LCA) of current systems, analyzing the future of indoor and vertical farming, determining the optimal conditions for farms to thrive, putting together a stakeholder working group, and conducting research with St. Louis (see page 20 for more on why St. Louis was selected) as the focus.

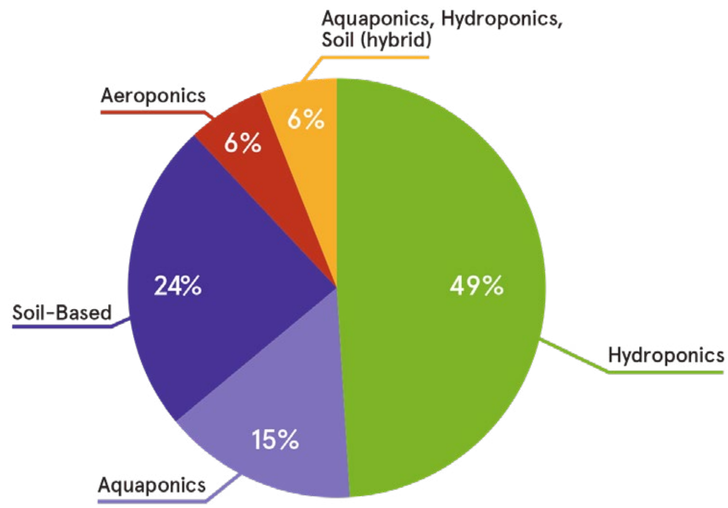
This research will be used to inform Phase II. In 2020, we will kick off the stakeholder working group that will use our Phase I research and their own expertise to begin designing a pilot system in St. Louis. This pilot will serve as a test case to see if there is a financially feasible way to scale the industry, growing a range of fruits and vegetables at competitive prices. The goal of Phase II is to produce a dynamic roadmap and a credible business plan as a group, so that when this project ends, key players are already invested and ready to move ahead with building a pilot system—one that can be replicated worldwide, making food production more environmentally sustainable.

CONTROLLED ENVIRONMENT AGRICULTURE INDUSTRY LANDSCAPE

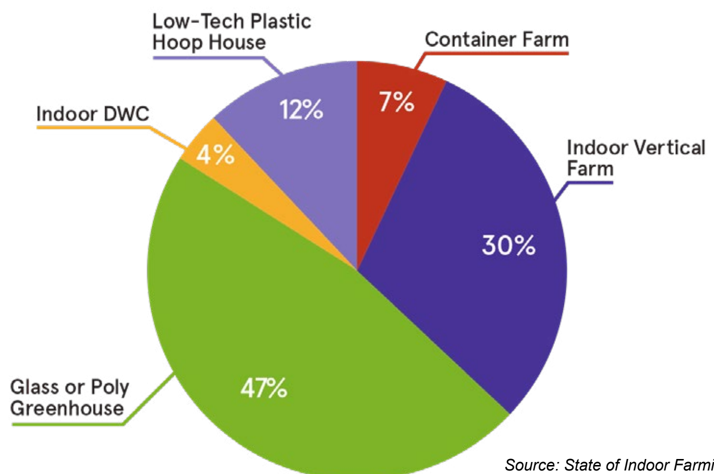
The indoor, soilless farming industry is attracting attention and money, growing quickly, and generating important benefits, but it remains a nascent, disparate industry with several key hurdles that must be addressed before it can achieve scale. There is no single definition of an indoor, soilless farm. These terms can encompass different technologies, including hydroponics, aeroponics (a subset of hydroponics using mist rather than running water), and aquaponics (a combination of aquaculture and hydroponics that raises marine life in a symbiotic system with plants). The growing is done either in greenhouses, mostly using sunlight but often with some artificial supplemental lighting, or in vertically stacked systems utilizing grow light systems. These farms can be in urban or rural areas and vary in size, presenting different challenges and business models. Collectively, this industry is referred to as controlled environment agriculture (CEA).

As noted above, CEA remains a disparate industry. While hydroponics makes up about half of all indoor farms (49%), significant minorities exist in aquaponics (15%), aeroponics (6%), and hybrid systems (6%). Nearly a quarter (24%) are using soil, though they are still controlling their environment in a closed system. These farms are also betting on different formats for controlling their environment, with farms in greenhouses, vertical systems, containers, and even sometimes simply hoop houses. Many farms are also developing their own proprietary technology, including LED lighting, water cooling systems, physical grow structures, and automation, meaning farms are getting pulled in all directions and there will be competitive challenges to scaling best practices as everyone attempts to invent their own wheels.

GROWING SYSTEM



FACILITY TYPE



Source: State of Indoor Farming. Agrilyst: 2017.

There is homogeneity, however, in what they grow. Nearly all farms are growing some type of leafy herb or green. While there is a significant minority growing tomatoes (16%), those are almost exclusively the domain of large greenhouses in the southwestern US or hoop houses using soil. Almost no vertical farms or urban-based greenhouses are in the fruiting produce space. This is because energy costs are high, and while nearly anything can be grown in these systems, it may not be cost effective or environmentally sustainable to do so. The energy needed to produce fruiting vegetables is often, though not universally, too significant at current cost per edible biomass. In fact, energy is one of the biggest hurdles facing the industry, representing around 25% of operating costs for vertical farms (but a lower 8% of greenhouse farms.)[1]

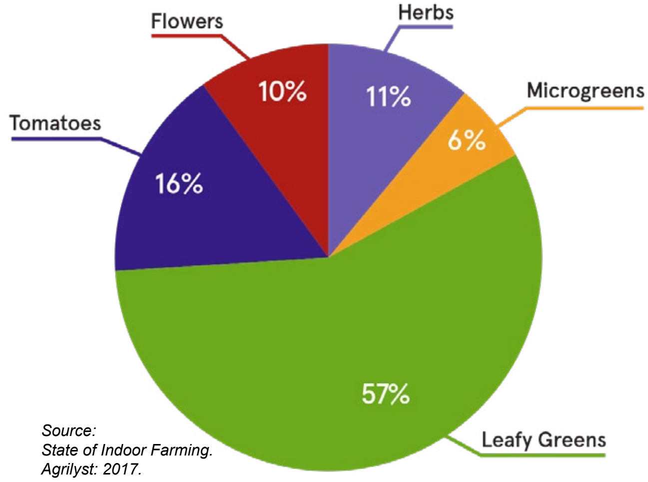
Vertical farming has only become popular, and feasible, with the rise of LED grow lights. They operate with far less energy, and far less heat, than previous grow lights. Their cost is also quickly dropping. However, they have still not advanced quite enough; energy costs remain a major obstacle for CEA farms, especially vertical ones, due to the cost of lighting and the amount of excess heat thrown off by the lights. This also ties directly into the economic viability of growing fruiting plants or other commodities. Since we do not expect the cost of energy to decline, energy use must be more efficient. See the *Life Cycle Analysis* section below for further discussion on the exact energy needs of these farms and the *Future of Indoor and Vertical Farming* section for innovations that might bend the energy curve.

LANDED COSTS OF 1 KG LETTUCE[2]

	FIELD	GREENHOUSE	VERTICAL FARM
NEW YORK CITY	3.04	8.09	7.82
CHICAGO	2.72	7.03	6.89

Right now, without further innovation or partnerships, produce grown in CEA systems is more expensive than produce grown with conventional methods, even when including the cost of shipping (although not including different levels of food waste).

MAIN CROP TYPE



Source:
State of Indoor Farming.
Agrilyst: 2017.

This is largely due to energy and labor. For example, transportation accounts for 67%-70% of costs for conventionally grown field lettuce shipped from Salinas, California, compared to just 12% for greenhouse and vertical farms.[3] (This scenario assumes greenhouses are located outside of a city, but if they are located inside a city, like Gotham Greens in Brooklyn or Chicago, those costs would be even lower.) However, CEA farms face significant input costs. For a greenhouse farm, labor and management, energy, and structures make up more than 80% of costs. Labor costs are higher not only due to the lack of automation and higher wage rates in cities, but also because of the administrative staff needed for management and marketing.[4] For large, established farms in California, less marketing is needed and management costs are spread across a much larger quantity of lettuce.

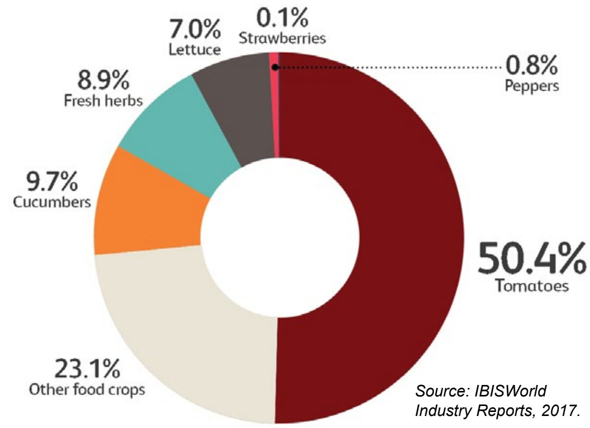
Despite these hurdles, the industry is growing. In 2017, hydroponic crop farming in the United States generated revenues of $848 million with annual growth of 3.4%.[5] The size mostly comes from a few major players, such as Houweling's Tomatoes (28.5% of market), NatureSweet Ltd (23.7%), and Village Farms International (11.2%), which are located in the southwest United States, grow in giant greenhouses, and ship across the country and beyond.[6] Tomatoes make up just over half (50.4%) of what they grow.[7] And, while grown hydroponically, most use mediums that mimic soil. There are some in this category, such as BrightFarms and Gotham Greens, which are growing with more innovative mediums and

1 *State of Indoor Farming.* Agrilyst: 2017.
2,3,4 Nicholson, Charles, et al. *Comparing the Costs and Environmental Impacts of Conventional and Controlled Environment Agriculture Leaf Lettuce Supply Chains.* Smart Marketing: 2019.
5,6,7 *Color me green: As consumers increasingly buy locally grown produce, revenue is expected to grow.* IBISWorld Industry Report: 2017.

in urban environments, and are commonly seen as part of the vertical farming industry due to their innovation and similar customer segments even though they do not stack their grow systems.

The vertical farming sector is growing even faster than all types of hydroponics combined. It is projected to have a combined annual growth rate of more than 24% during 2018-2024, reaching $3 billion in revenues worldwide by 2024.[8] Some of the biggest players include Aerofarms, Plenty, Green Spirit Farms, and Bowery Farming.

PRODUCE GROWN HYDROPONICALLY



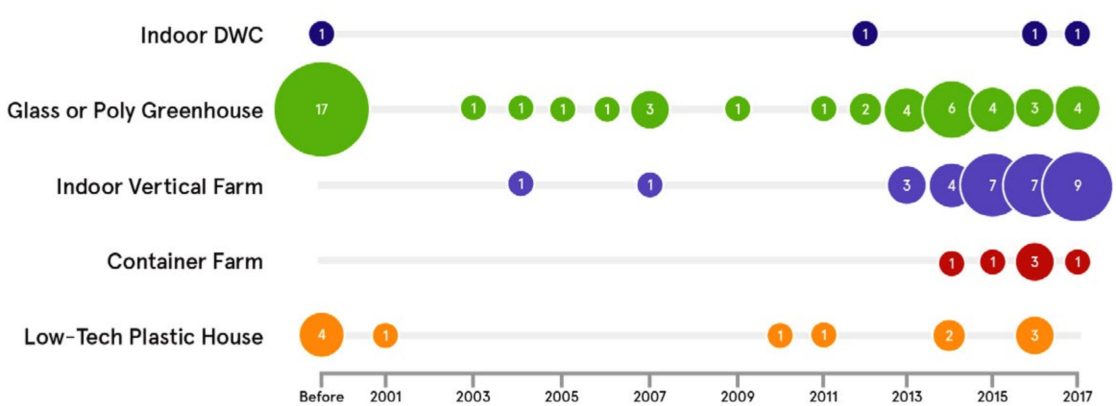
Source: IBISWorld Industry Reports, 2017.

The industry continues to grow quickly in number of farms, too. While large, hydroponic greenhouses have been operating in the southwestern US for a while, there are now an increasing number of vertical and greenhouse farms opening across the country, with a focus in and around cities. They are generating excitement and raising significant capital investment. Some of the biggest equity raises in just the last year include Infarm with $100 million, Plenty with $200 million, AeroFarms with $100 million, and Bowery with $90 million, but there are many others raising significant sums and some of these same farms garnered large investments in previous years, too. AgFunder estimates that since 2017 nearly $600 million has been invested in vertical farms alone, not including start-ups that use greenhouses like BrightFarms and Gotham Greens.[9]

There are many reasons that this industry is attracting excitement and capital. Consumers are becoming increasingly discerning about their food, demanding fresh, local, and organic products, while still expecting access to fresh food with little change in eating habits year-round. Companies are interested in securing supply chains that might be at risk due to climate change. And, food safety is becoming more of a concern and could significantly boost interest in the industry. On November 22, 2019, the US Centers for Disease Control and Prevention (CDC) warned that 40 people in 16 states had been sickened by romaine contaminated with E. coli and that all lettuce from Salinas, California should be discarded. (This is in addition to a similar warning issued just two days before Thanksgiving 2018.) However, in their recent announcement, the CDC noted that this warning did not extend to lettuce grown "from places other than Salinas, or labeled as indoor, or hydroponically- or greenhouse-grown." With individual, tightly-controlled farms, ensuring food safety, and its associated food waste, could be a key differentiator.

We are eager to explore possible next steps to build on some of these advantages and boost all CEA farms.

FARM OPENINGS BY TYPE



Source: State of Indoor Farming. Agrilyst: 2017.

8 *Color me green: As consumers increasingly buy locally grown produce, revenue is expected to grow.* IBISWorld Industry Report: 2017.
9 Tasgal, Peter. *The Economics of Local Vertical and Greenhouse Farming Are Getting Competitive.* AgFunder News: April 3, 2019.
10 Sun, Lena H. *Don't eat romaine lettuce from California's Salinas Valley, CDC Warns.* Washington Post: November 23, 2019.

LIFE CYCLE ANALYSIS SUMMARY

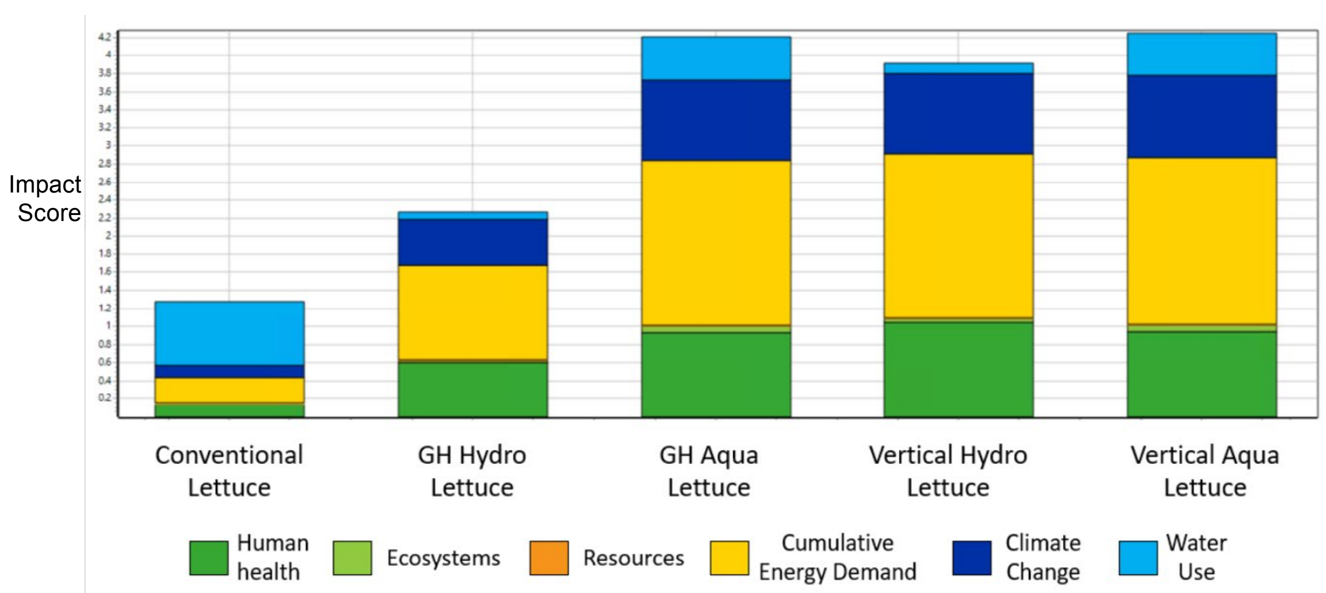
The full Life Cycle Analysis report can be viewed in Appendix I. This report examines the different food production systems solely through an environmental lens and does not consider other factors like social and economic impacts.

The purpose of this Life Cycle Assessment (LCA) is to quantify the total environmental impacts of CEA and conventional agriculture to determine which production system is more environmentally sustainable. This LCA compares the environmental impacts of conventional agriculture and four types of indoor agriculture systems—combinations of two different production methods and two different growing environments—to produce one kilogram of romaine lettuce that is packaged and transported to a grocery store in St. Louis. We used a single-score comparison with six grouped themes of impact areas to compare the five agricultural systems.

Our results show that conventionally grown lettuce produced in California and transported to St. Louis has the overall lowest environmental impact, though this may change as CEA technology improves and climate change makes conventional agriculture more challenging. After conventional lettuce, greenhouse hydroponic lettuce grown in St. Louis and distributed locally has the next lowest environmental impact.

There were three main impact areas that WWF identified as important in the beginning of the study: contribution to climate change, land use, and water use. In these three categories, conventional agriculture has the lowest impact associated with climate change, primarily because of its lower electricity footprint and cleaner mix of electricity in California. However, greenhouse hydroponic agriculture received the lowest scores for land use and water use with vertical hydroponics in second place, and then conventional agriculture. It is important to note that this does not include an analysis of larger indirect environmental consequences, such as damage caused by dams.

PRODUCE GROWN HYDROPONICALLY



Of the other impact areas, the four controlled environment agriculture systems all had higher impacts on human health and ecosystems relative to conventional agriculture. The primary driver is the systems' different electricity usage and grid mixes. In addition to higher GHG emissions per kilowatt hour, the St. Louis electricity grid has higher ecosystem and human toxicity level impacts than California electricity.[11]

The two aquaponics systems show much higher environmental impacts than the other three systems. We allocated the environmental impacts based on the relative economic value of production and calculated an allocation of 75% of impacts going to lettuce and 25% of impacts going to tilapia. The main drivers for the environmental impacts in aquaponics, apart from electricity, come from tilapia feed, which particularly contributes to land and water use.

Of the two hydroponics systems, greenhouse hydroponic lettuce has a significantly lower footprint than vertical hydroponic lettuce across all six impact areas. The main driver of this difference is vertical agriculture's higher electricity use due to using LED lights as its primary source of plant light.

One reason that the four CEA systems had higher environmental impacts than conventional agriculture is because of CEA agriculture's higher electricity use. We modeled a hypothetical scenario where the electricity use for all five systems is sourced from US photovoltaic solar power instead of the standard regionally specific mixes. In this model, greenhouse and vertical hydroponic systems have overall lower environmental impacts than conventional agriculture, with drastically lower impacts on human and ecosystem health. This suggests that either hydroponic system would be a more environmentally sustainable choice than conventionally grown lettuce if the farm is able to directly source solar electricity, or else pay to receive solar credits.

With current technology efficiency, electricity sources, and natural resource availability, conventional agriculture has the lowest total environmental impact of the five agricultural systems that we modeled. However, if hydroponic farms source their electricity from renewable sources such as solar or wind, which is increasingly available in Missouri, instead of the standard regional mix used by St. Louis, then both greenhouse and vertical hydroponic farms would have lower environmental impacts than conventional agriculture. Another possible option is to make use of some of St. Louis's stranded assets, such as power plants, by partnering with electricity plants to use surplus energy during certain times of day, allowing the plants to produce energy more uniformly and therefore more efficiently.

A greenhouse hydroponic farm would be the most environmentally sustainable choice out of the indoor soilless farming options for the St. Louis region for the foreseeable future, until LED technology can make significant efficiency gains to reduce the energy footprint of vertical agriculture. Situating the greenhouse on otherwise unused space like a building roof or brownfields could further decrease the environmental impacts of greenhouse hydroponic agriculture by reducing its land-use footprint and/or competition for space.

11 Ecoinvent 2018.

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THE FUTURE OF INDOOR AND VERTICAL FARMING

While the LCA took a snapshot of the environmental footprint of different types of indoor soilless farms today, we also examined new technologies and innovations that are coming down the pipeline. This is a new industry with quickly changing technology. As more money enters this space, it will incentivize more companies to tackle some of the challenges facing the industry. However, they may still be thinking as individual farms rather than as an industry that could partner and make use of existing systems, such as stranded or under-utilized assets. We want to build upon what is already happening to see if there are further ways to tackle some of the hurdles. One of the biggest hurdles remains the use of energy, but there are already innovations attempting to bend the cost curve to be able to grow more types of food in more locations at affordable prices.

Right now, nearly all vertical farms are powered by LEDs, but the technology is swiftly changing.

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LIGHTING

LEDs have made vertical farming a possibility. They are low in radiant heat and can therefore be placed near a growing plant without risk of burning it, making them more suitable than previous grow lights for vertical farms with closely spaced shelves. They are also more energy efficient and allow for optimization of light as they are easily scaled up and down as lighting needs change. Already, LED lights can be synced with a crop's growth to minimize energy use and optimize yields, providing more targeted spectrums and amounts of light for photosynthesis. The technology is also improving quickly, with a 40% increase in efficiency over the last five years. However, there still may be additional gains as the spectrum of light from LEDs is far more than that utilized by plants. Reducing this "waste" would reduce costs as well as unnecessary heat in the system.

First, there are fairly simple modifications that can be made to improve and reduce electricity costs. For example, reflectors can be installed to increase the ratio of light and improve light quality.[12]

12 Martin, Michael and Molin, Elvira. *Reviewing the energy and environmental performance of vertical farming systems in urban environments.* IVL Swedish Environmental Research Institute, No. C 298: March 2018.

Second, the LED lights themselves may continue to increase in efficiency. While some people believe there is little more to be gained as there is only a finite amount of light on any spectrum,[13] many believe otherwise. Some practitioners and academics believe that there are developments being made that could increase LED efficiency exponentially. Right now, LED technologies provide 28% efficiency and it is estimated that this would need to improve to 50-60% for indoor farming to become cost-effective for a variety of crops.[14] Experimental developments have already reached this mark. Dutch lighting engineers at Philips have produced LEDs with 68% efficiency, which would dramatically cut energy costs and the environmental footprint of these farms.[15] Meanwhile, PlantLab, a Netherlands based group, recently invented a lighting technology that would provide the optimal wavelength for plant growth. Unlike traditional assimilation lighting and fluorescent lighting, LEDs only emit one light color. The new lighting technology provides the exact wavelengths needed for photosynthesis – blue, red, and infrared light – so no energy is wasted with light spectra that are not used by the plant. This would help to grow food with a smaller energy footprint.[16] PlantLab is already using this technology on their farms.

There are also advances happening in combination with LEDs. Netled, a company based in Finland, has developed a new patent-pending water-cooled LED light that can be combined with a heat recovery system. They use automation to keep the growing environment optimized and, in a country where electricity prices can vary hourly, they use their algorithms to adapt conditions to current economics, saving on energy costs.[17] This technology isn't proven yet but it, or other similar innovations, could significantly change the economics and environmental footprint of vertical farming.

FIBER OPTIC TECHNOLOGY

Optical fibers are commonly used in many applications, such as imaging, lighting, and sensing. However, there has been limited exploration of using them for daylighting (channeling outdoor natural light indoors) in indoor farming. This can be accomplished by using a solar collector that is either active or passive, coupled with optical fibers made from polymer or silica, to transmit natural light deep inside a building or underground. The technology has even been used to tunnel sunlight up to 40 meters into the ground.[18] A subset of this, the hybrid lighting system (HLS), uses artificial light to support daylighting, producing consistent lighting levels through controlled dimming. The technology is still too expensive when combined with LEDs and doesn't produce enough light on its own to grow plants commercially, but it is still developing and may eventually challenge or replace electric grow lights.[19] Technology like this would also make it possible to grow food in the caves in and around St. Louis, which is a potentially energy-efficient option discussed on page 15.

AI AND MACHINE LEARNING

AI and machine learning are also being used in various combinations on farms to optimize growing conditions and improve efficiency. Some farms in Japan, where vertical farming is quite popular since the country imports 60% of its food, are combining custom-designed LEDs with AI. They are collaborating with NTT West, a telecommunications company, on using an AI program to analyze production data and boost yields without increasing energy use. While these systems are currently quite expensive and unproven, the Japan Research Institute expects that within five years, these technologies will bring production costs down enough to compete with outdoor farms.[20] Right now, 60% of indoor farms in Japan are unprofitable, largely because of high energy use and cost. Most turn a profit because of government subsidies or by charging a premium to consumers for organic, fresh vegetables.[21] Japan is continuing to invest in technology that could change that curve, however, and is motivated to produce more of its own food.

13, 17, 22 Hughes, Sarah. *Vertical farming: does the economic model work?* The Nuffield Farming Scholarship Trust: July 2018.

14, 15, 16 Al-Kodmany, Kheir. *The Vertical Farm: A Review of Developments and Implications for the Vertical City.* Department of Urban Planning and Policy, College of Urban Planning and Public Affairs, University of Illinois at Chicago: February 5, 2018.

18 Asiabanpour, Bahrma et al. *Optimizing Natural Light Distribution for Indoor Plant Growth Using PMMA Optical Fiber: Simulation and Empirical Study.* Journal of Renewable Energy Volume 2018, Article ID 9429867: June 3, 2018.

19, 23 Moon, Emily. *The farms of the future for outer space. Will they work on earth?* Pacific Standard: August 14, 2019.

20, 21 Takada, Aya. *As high-rise farms go global, Japan's spread leads the way.* The Japan Times: November 1, 2018.

PLANT BREEDING AND GENE-EDITED OR GMO SEEDS

Currently, nearly all seeds are optimized for outdoor growth, but some companies are now beginning to design seeds to grow in CEA systems and even thrive under LED lights. Developments could include breeding for uniform and early fruiting, rapid biomass and multi-harvest capability, photo-induced quality traits (i.e., using LEDs to change color or flavor), and auto-harvest plant architecture (i.e., conducive automated harvesting.) These could all help in reducing energy costs or increasing yield to offset energy cost and use. Major players like Bayer and numerous start-ups are exploring this space, but they are in very early stages. Government players are also showing interest. The Foundation for Food and Agriculture Research (FFAR) launched a public-private partnership, Precision Indoor Plants (PIP), in 2019 to produce seeds for indoor growth that are optimized for flavor and nutrition. They will start by focusing on blueberries, cilantro, lettuce, strawberries, and tomatoes and have brought together a coalition of stakeholders. Currently, AeroFarms, BASF, Benson Hill Biosystems, and the Japan Plant Factory Association are collaborating, but they expect to grow this partnership to 15 entities. While they are not specifically examining optimization for energy use or higher yield, their Director of Scientific Partnerships, Dr. Kashyap Choksi, expects this to be a consideration as well.

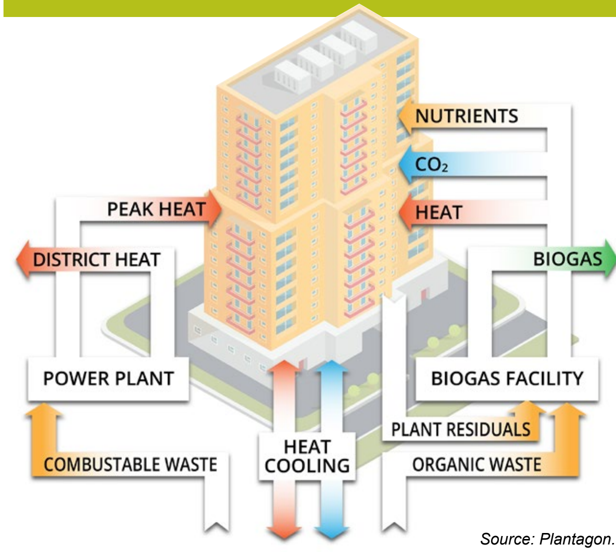
RENEWABLE ENERGY

Many farms are also experimenting with using renewable energy. So far, this has been quite expensive and potentially an inefficient use of resources. For example, Dr. Bruce Bugbee, Professor of Environmental Plant Physiology at Utah State University and past Chairman of the Crop Physiology Division of NASA, estimates that five acres of solar panels would be needed to power enough light for one acre of an indoor farm. However, the cost of solar panels is quickly decreasing at the same time their efficiency and yield is increasing. The trade-off could change in the future and, even now, depends deeply on where a farm is located and what renewable energy, or stranded assets, are available. In late 2019, Plenty opened a new farm, Tigris, in south San Francisco that they say is fully powered by renewable energy – half solar, half wind. While this farm is brand new and the economics are still largely hypothetical, they are not the only farm breaking new ground. Some vertical farms have implemented wind turbines to supply power. Other systems, such as thermal systems to collect heat and warehouse refrigeration exhaust, are under design or consideration. It is likely that many will fail, but gains could also be significant.

CO-LOCATION, CO-GENERATION, AND SYMBIOTIC SYSTEMS

Few, if any, farms have successfully integrated their systems by co-locating next to a stranded or underutilized asset, but some are beginning to explore this space, where there could be significant opportunities. Plantagon, a former but now closed indoor farming design and consulting company headquartered in Stockholm, designed a symbiotic system that would integrate municipal infrastructure such as heating, biogas, waste, water, and energy with food production (see below). This only exists on paper but would use "waste" generated from the municipal functions to create a highly efficient growing system. It would also feed the plant residuals back into the system, utilizing anaerobic digestion to create biogas and decreasing food waste. As technology improves, overall system prices go down, and municipal players become interested in this space, this kind of integration could be a viable approach to vertical farming and reducing energy use.

One way a food production system could integrate with municipal systems



Source: Plantagon.

While still far from a fully symbiotic system, Great Northern Hydroponics in Quebec, Canada, is currently using a cogeneration machine that reduces its heating costs and reliance on fossil fuels. Its power production has increased and it is capable of selling electricity back to the Ontario Power Authority, generating revenue.[24] This is a location specific set-up. They are using greenhouses in Canada, where it would be prohibitively expensive to heat a greenhouse. By co-locating, they are capturing excess heat from a power plant and recycling it into their system. This is the opposite problem of a vertical farm, which typically has excess heat, but still serves as an important example of the possibility of co-generation and co-location.

There are other farms experimenting or theorizing about co-locating next to producers of excess heat or energy. Once again, this is location dependent and interests would have to align to ensure receipt of excess capacity at optimal times for the farms. Agriport A7, an indoor farm in the Netherlands was built adjacent to an 11-hectare Microsoft server hub, where it will receive Microsoft's excess heat to warm its greenhouse. This same set-up could also apply to Combined Heat and Power (CHP) plants. It is also possible that a vertical farm, which does not need heat, could capture excess heat from a CHP plant and excess heat from its own facility and use that heat to produce energy. Again, this is only theoretical at this point but is worth considering as technologies improve and cost curves change. It could also be explored as part of an innovative financing model for these capital-intensive farms.

Carbon Capture Technology could also be used depending on the location of a farm. If co-located in advance, this technology could be used to capture excess CO_2 from a site and then pump it directly into the growing system. This would capitalize on naturally occurring CO_2 and recycle it, rather than releasing it directly into the atmosphere.

UNDERGROUND FARMING

Many vertical farms, unlike greenhouse farms, struggle with excess heat. Underground farming could be advantageous in those circumstances since the depth regulates ambient temperatures and provides a naturally cooler atmosphere.[25] Subterranean farms use the earth's thermal mass to buffer temperatures. For example, mushrooms grow underground quite well with minimal energy; they prefer damp, cool, and dark places. St. Louis has a history of growing mushrooms in caves. However, the variety and value of mushrooms on today's markets create an entirely different market opportunity. Produce is not quite as natural a fit, but since vertical farms use 100% artificial lighting anyway, the darkness is not a hurdle and the constant air temperature and humidity levels, as well as CO_2 and water supply, tunnels, caves, and shafts used for vertical farming would likely use less energy than facilities aboveground.[26]

Several countries have demonstrated their interest in and ability to vertically farm underground. In England, 100 feet below the streets of London, Growing Underground produces two tons of food per month using a WWII air raid shelter as an underground farm. They are growing exotic herbs and shoots, including pea shoots, rocket/arugula, garlic chives, red vein sorrel, Thai basil, and some edible flowers. They also grow miniature vegetables with plans to expand to heritage tomato varieties and mushrooms.[27]

© Lance Cheung/USDA

24 Al-Kodmany, Kheir. *The Vertical Farm: A Review of Developments and Implications for the Vertical City.* Department of Urban Planning and Policy, College of Urban Planning and Public Affairs, University of Illinois at Chicago: February 5, 2018.

25, 27 Russo, Julianne. *The Urban Underground Farming Solution.* The Borgen Magazine: January 11, 2019.

26 Lloyd, Matt. *Old coal mines can be "perfect underground food farms.* BBC: December 2, 2018.

In Wales, farmers are exploring the use of abandoned coal mines. The industry collapsed in the 1980s, but advocates see indoor farming as an opportunity to re-use these stranded assets. So far this is entirely theoretical, but it is being explored as a way to not only grow food sustainably but to generate income and jobs in an area with high poverty and unemployment.[28]

Cycloponics, in Paris, has situated their 37,700-square-foot farm in an abandoned parking garage located beneath an affordable housing complex. They are using hydroponics to grow microgreens, mushrooms, and chicory (a root requiring no natural light).[29]

In Sweden, Plantagon CityFarm built an underground farm housed in an old newspaper archive underneath a Stockholm office tower. They grow food and use the ambient energy generated by the LEDs to heat the office building above.[30] And, in Den Bosch in the Netherlands, PlantLab built a three story underground vertical farm. Using advanced LED technology and a variety of automation and monitoring systems, they claim to not only save on energy costs, but produce a yield three times the amount of the average hydroponic greenhouse.[31]

While underground farming is quite new, St. Louis caves may make excellent candidates and could allow a farm to decrease its energy footprint while making use of another type of stranded asset.

WASTE AND RECYCLING

While much of the innovation in vertical and indoor farming is around energy and automation, there are also opportunities to increase environmental sustainability and develop new revenue streams around waste and recycling. While these farms use far fewer resources than conventional farming, with the exception of energy, there is still waste in other areas, such as water and the inedible parts of plants.

Indoor, soilless farms use a fraction of the water used in conventional agriculture, but still need to expel their wastewater periodically. There is no consensus on what to do with the water and many farms simply dump their nutrient-rich water into fields or drains. However, there are three techniques for recycling this water that are currently being explored. The first is drainage water recycling, wherein the water is stored in fields and used to irrigate crops. This makes use of its already nutrient rich content. The USDA is pioneering this in their Transforming Drainage project.[32] The second method is potable reuse, or water that is cleaned to the point of human consumption.[33] However, this is expensive and requires additional infrastructure. Finally, the Water Research Foundation is exploring extracting the nutrients from the wastewater (also known as biosolids) and then reusing those nutrients for fertilizers or land applications.

The industry can learn from other producers with similar problems. In its desire to produce net-zero-carbon milk, Fair Oaks Farm in Indiana has, among other strategies, built a state-of-the-art methane biogas digestor. In addition to methane, compressed natural gas, and electricity, they are capturing anhydrous ammonia, nitrogen, phosphorus, and solids from their waste stream to use on their own fields and sell to neighboring farmers. This technology could be applied to capture nutrients in a cost-effective way. The advantage of this form of capture is that it allows the end user to apply

28, 29, 30 Russo, Julianne. The Urban Underground Farming Solution. The Borgen Magazine: January 11, 2019.

31 Al-Kodmany, Kheir. *The Vertical Farm: A Review of Developments and Implications for the Vertical City.* Department of Urban Planning and Policy, College of Urban Planning and Public Affairs, University of Illinois at Chicago: February 5, 2018.

32 *Drainage Water Recycling.* Transforming Drainage, USDA: 2019.

33 Angelakis, Andreas N, et al. *Water Reuse: From Ancient to Modern Times and the Future.* Frontiers: May 11, 2018.

the right amount of nutrients, rather than just applying a liquid that could vary considerably and be hit or miss in terms of a crop's needs at the time.

There are also potential markets for recycled biomass, the organic matter leftover from these farms. Right now, since they largely grow leafy greens, the edible biomass harvested makes up most of the biomass produced. However, some inedible or damaged parts, as well as root systems, are discarded. If fruiting vegetables and fruits are eventually grown, such as tomatoes, there would also be stems and plants to discard. There are numerous ways this waste could be re-used, such as mulching it[34], recovering nutrients to be used as fertilizer[35], or even turning the biomass to ash and using that as fertilizer or for geotechnical and industrial purposes.[36] Experiments have shown that up to 70% of the nutrients in the inedible biomass can be recovered for use in fertilizer- a number that could increase more in the future.[37] Fair Oaks Farm is already capturing 90-100% of nutrients from manure in combination with plant waste in digestors.

Perhaps most intriguingly, there is also the possibility of using that inedible biomass to create energy. In other industries, digested organic wastes are already being used to produce renewable methane and compressed natural gas.[38] It is possible that vertical farms could use their own organic waste for this purpose, lowering their energy cost and environmental footprint. So far, the process to convert waste to energy is costly and inefficient, but many companies and universities are working to improve the process with some potentially ground-breaking successes.[39] While it may not be a perfect solution at this time, with so many resources going toward this problem, this approach is likely to continue to improve.

These are just some of the innovations happening in or affecting the indoor, soilless farming industry. Other technologies not discussed here are also improving and will bring down the operational costs of these farms. With advancements in multi-racking mechanized systems, solar power, wind power, storage batteries, drones, computing power, software applications, databases, and The Internet of Things, decreasing energy costs and increasing yield and efficiency will likely continue to shift the landscape of indoor and vertical farming.

Further, if we consider changes to business models and other factors, there is a wide range of possibilities that could affect the efficacy of these systems. If climate change impacts California production and other regions more quickly than expected; if renewable energy becomes standard; if communities value local food production, the elimination of food deserts, and job creation; or if new business models that assign different weights and values than current production systems are considered, then we could see value in local production and some systems might become more attractive.

34 *Sustainability.* Eufloria Flowers: 2017.
35, 37 Lunn, Griffin M, et al. *Recovery of Nutrients from Inedible Biomass of Tomato and Pepper to Recycle Fertilizer.* 47th International Conference on Environmental Systems: July 16, 2017.
36 Insam, Heriber and A. Knapp. *Recycling of Biomass Ashes: Current Technologies and Future Research Needs.* Recycling of Biomass Ashes, Springer: 2011.
38 Cuello, Joel. *New York City Needs More Vertical Farms: Urban Growth on a Higher Plane.* New York Daily News: Oct 1, 2019.
39 Stahl, Lesley. *The Unlikely, Eccentric Inventor Turning Inedible Plant Life Into Fuel.* 60 Minutes, CBS News: Jan 6, 2019.

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TECHNOLOGIES AND OPTIMAL CONDITIONS

Indoor, soilless farming encompasses a variety of growing techniques and tools. There are few best practices, many considerations, and the technology is rapidly evolving. Choices around technology, systems, and crops also affect where a farm should be located and what opportunities and hurdles will be most important. In our full report, we have included an in-depth explanation and analysis of each type of system, the various technologies that are required or suggested with pros and cons, and the ideal growth conditions for several popular crops. This report is meant to serve as a resource for the Stakeholder Working Group (see below) as decisions are made about where to situate a farm, what system and technology to use, and what to grow. ***See Appendix II for the full report.***

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STAKEHOLDER WORKING GROUP

The stakeholder working group includes a wide variety of participants from all different disciplines. Participants include, but are not limited to, representatives from major businesses (grocery stores, agriculture companies), entrepreneurs and accelerators/incubators in the indoor/vertical farming spacing, universities leading research in this field, and civic and community groups. Throughout 2020, this group will meet to engage in research and discussions, explore partnerships, and inform and assist in the development of a dynamic business roadmap and pilot design. WWF's Markets Institute will convene this group to promote creative and uncommon collaboration to hopefully overcome challenges facing the industry and lead to a scalable pilot. To learn more about the participants and discuss involvement, see contact details on page two.

ST. LOUIS RESEARCH

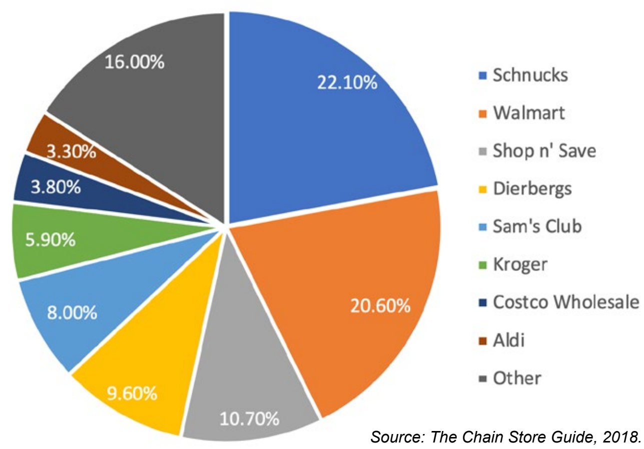
St. Louis is a strong candidate for indoor soilless farming. It has a metropolitan statistical area (MSA) with 2.8 million people and very hot summers and cold winters, limiting the growing season and providing demand for food year-round. It also has thermal power plants, USPS distribution hubs, strong universities, community finance options (trusts/foundations), policy incentives for urban farming, existing grocery infrastructure, and potential community, research, and purchasing partners. St. Louis also possesses some unique assets; for example, St. Louis, has myriad caves that were once used for brewing beer, growing mushrooms, document storage, and mining. Today, many are sitting vacant and could be potential energy-efficient and temperature-stable sites for urban soilless farms.

MARKETS

The St. Louis grocery market is diverse, with several major players. Schnucks and Walmart lead the group (see chart, right). This market includes all grocery sales, but fresh produce is a major draw and continues to grow.

Consumer demand for local food continues to increase across the United States, and St. Louis is no exception. The Economic Research Service (ERS) estimates that US local food sales exceeded $6.1 billion in 2012, with nearly 8% of US farms participating in the local food trade.[40] The ERS also indicates that the share of farms participating in local food markets trends even higher in parts of the country where smaller-scale and produce farmers predominated.[41] St. Louis already has some small produce farms that contribute to positive public interest in locally-sourced foods and continue to build demand for this market. Sales of locally grown produce in the St. Louis area (encompassing a 120-mile radius around the city) were estimated at $176 million in 2017, including 71% in retail and 29% in food service. This market continues to increase in size and grew around 14% annually from 2014 to 2017.[42]

ST. LOUIS AREA GROCERY MARKET SHARE



Source: The Chain Store Guide, 2018.

The demand for local food appears to include food grown indoors or vertically in soilless systems, even though this is a new format for many consumers and is still not widely known. According to the Food Marketing Institute's *Power of Produce*, about one-third of shoppers have little to no knowledge of hydroponically grown produce, but views among the two-thirds who have an opinion are very positive.

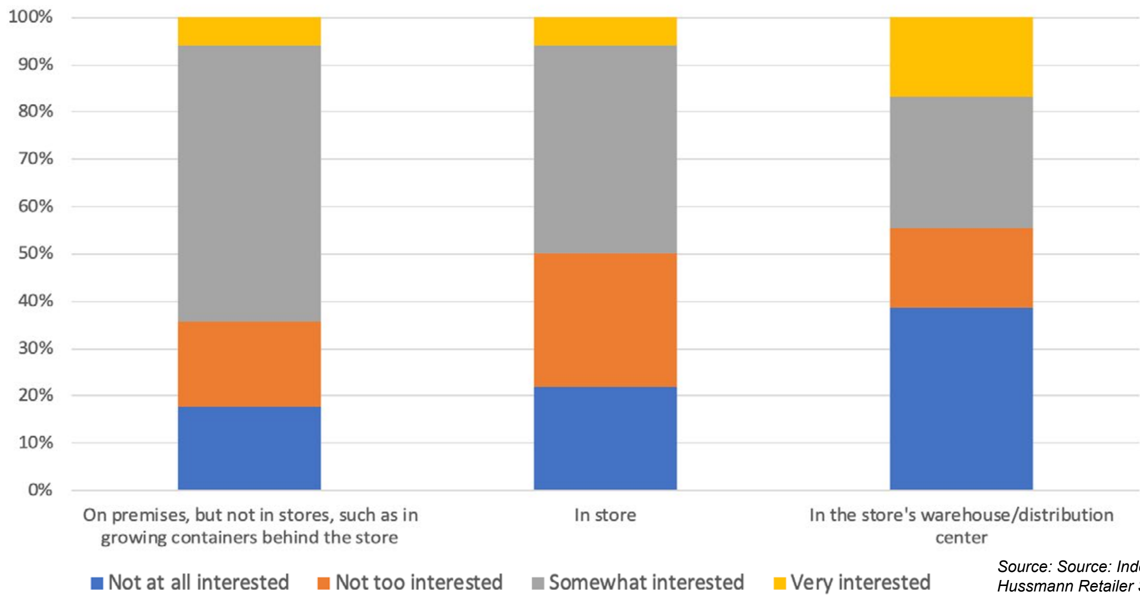
SHOPPER PERCEPTIONS OF HYDROPONICALLY- OR GREENHOUSE- GROWN PRODUCE VS. REGULAR PRODUCE

	AGREE	DISAGREE
NUTRITION IS EQUALLY GOOD OR BETTER	60%	9%
CAN QUALIFY AS GROWN LOCALLY	60%	10%
TASTE IS EQUALLY GOOD OR BETTER	56%	11%
CAN QUALIFY AS GROWN ORGANICALLY	56%	10%

Source: Power of Produce 2019.

40 *Harvesting Opportunity - The Power of Regional Food System Investments Opportunity to Transform Communities.* Federal Reserve Bank of St. Louis: 2017.
41 *Growing a St. Louis Local Sustainable Food Market – What Is & What Must Happen Next.* Mintel Consulting: 2018.
42 Saksena, Michelle J, et al. *America's Eating Habits: Food Away from Home.* US Department of Agriculture, Economic Research Service: September 2018.

RETAILER INTEREST BY INDOOR FARMING MODEL



Source: Source: Indoor Growing – Hussmann Retailer Survey, 2018.

Consumers are not the only ones interested in buying locally grown produce from indoor, soilless farms. In a small survey of decision makers at major grocery stores, 65% are very or somewhat interested in growing food on the premises. Some of this interest is due to changing consumer demands and building a competitive advantage, but some is also focused on reducing food miles and food storage time to reduce costs and waste. Buyers are most interested in focusing on produce with the shortest shelf-life. This could not only reduce cost to stores but increase demand since more consumers might be interested in purchasing a wider variety of produce if it is less likely to spoil before using at home.

Some St. Louis retailers are already entering this space. Maddie Earnest, co-owner of Local Harvest, a natural and local food marketplace, believes there are significant growth opportunities for suppliers of local produce. Her store sales have increased for the last two years. She reports that Old Tyme Produce is actively looking for more local produce suppliers and that Sunfarm, a local produce distributor, wants to be more in this space but previously found it difficult to scale up local sourcing operations. Earnest is excited about the ability of soilless, indoor farming to reduce dependence on good quality soil, increase opportunities for farmers, and provide local produce through the winter.

Meanwhile, Schnucks is already speaking with indoor farm operators about potential partnerships and pilots. According to Mike Tipton, VP, Produce, right now there is a premium to purchase locally grown greens or vine produce. However, as demand for these products increases, he hopes to see efficiencies in operation that help drive those costs down. Even right now, he sees other benefits. For example, indoor farming can provide a protected environment which could help minimize food safety issues, such as the numerous E. coli outbreaks linked to romaine lettuce. Tipton envisions a farm footprint that could be expanded in phases as Schnucks markets and drives awareness to consumers.

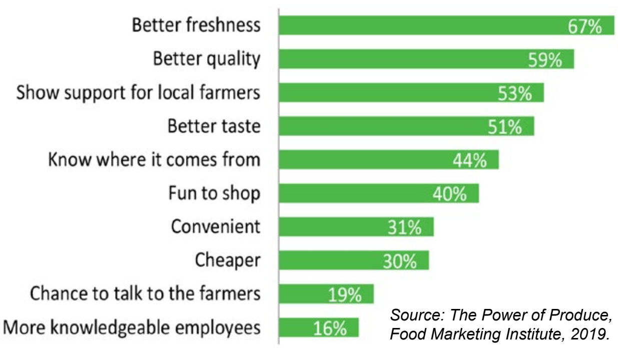
Many of these mainstream markets are also looking at locally sourced produce as a value-add and differentiator as the produce market continues to fragment. For example, fresh produce is becoming available in more and more stores. More than 20% of shoppers already purchase fresh produce at dollar, drug, and convenience stores. These numbers are still low, but significant enough to encourage traditional retailers to find a competitive advantage. Consumers are also increasingly turning to online purchases. Half of all shoppers have purchased at least some food items online. While fresh produce is still less common in this space, that is likely to change in the future as the total share of shopping continues to shift in this direction. All of these forces will continue to push retailers to innovate.

43 Earnest, Maddie. Personal interview: November 4, 2019.
44 Tipton, Mike. Personal interview: October 2, 2019.
45,46 Food Marketing Institute. *The Power of Produce.* The Food Marketing Institute, 210 Analytics. p. 26: 2019. Retrieved from: https://www.fmi.org/forms/store/ProductFormPublic/power-of-produce-2019

DISTRIBUTION CHANNELS

In addition to the changes in the traditional market, consumers are also no longer limited to purchasing from any form of store. There are an increasing number of distribution channels for supplying locally sourced produce directly to consumers. Farmers markets and community supported agriculture (CSA) are growing in popularity and providing consumers a closer connection to their food. Consumers choose to purchase produce from these channels because they believe that the food is fresher, with higher quality and better taste, as well as to show support for local farmers. These characteristics would also hold true for indoor, soilless farms.

REASONS FOR PURCHASING PRODUCE AT FARMERS MARKETS



Source: The Power of Produce, Food Marketing Institute, 2019.

Farmers markets and CSAs are also limited in their appeal, however. Farmers markets typically have limited hours and the majority are only open seasonally. CSAs have the same limitations, but also provide little or no choice in the produce that is sent to the consumer. These drawbacks constrain growth in these markets. Nearly all consumers (99.5%) still report that they get most of their fresh produce from food retailers or food service providers.[47]

These constraints also hold true for farmers. Most local food still reaches consumers through non-direct sales channels. According to the US Department of Agriculture's ERS, 54.8% of local food sales in 2012 were generated by farms that marketed all their local production through intermediaries, compared to fewer than 20% that used direct-to-consumer channels exclusively.[48]

There are some start-ups that are working to change this model, including in St. Louis. Foodshed.io is an aggregator using technology, specifically a marketing app and logistics platform, to connect small-scale producers with area restaurants, supermarkets, and institutional buyers. In 2018, the Missouri Coalition for the Environment connected Foodshed.io with several farmers in the St. Louis region to help them sell to Schnucks. The Coalition is hopeful that this pilot program will build support for local farmers and help broaden potential markets.[49] It is not only quite difficult for independent, small farmers to sell into large chains like Schnucks, but it is also hard for retailers to work with independent, local farms that may not meet their minimum amounts or food inspection requirements.

Another start-up, Native, is also now operating in St. Louis but works on building connections in the opposite direction, helping businesses find suitable local farmers or new products. For example, they worked with a multi-unit restaurant group to trial a local product before fully introducing the ingredient as part of a new salad offering.

Large intermediaries are also exploring this space. Even major distributors, like US Foods, struggle with sourcing channels. Matt Roy, formerly Senior Director of Produce at US Foods, says that the distributor was exploring options to partner with or source from vertical farms in NJ since the farther east you go, the more freight costs and so the more attractive it becomes to explore vertical farms. He says there is ongoing interest in sourcing from indoor farms to improve consistency in their current supply chain that is susceptible to weather patterns and events.

47 Food Marketing Institute. *The Power of Produce.* The Food Marketing Institute, 210 Analytics. p. 26: 2019. Retrieved from: https://www.fmi.org/forms/store/ProductFormPublic/power-of-produce-2019
48 *Harvesting Opportunity - The Power of Regional Food System Investments Opportunity to Transform Communities*. Federal Reserve Bank of St. Louis: 2017.
49 Miller, R., & Vatterott, M. *St. Louis Farm to Institution Feasibility Study.* Missouri Coalition for the Environment: 2019. Accessed at: https://moenvironment.org/wp-content/uploads/2019/05/MCE-STLFPC-Feasibility-Study-4.4MB.pdf
50 Interview with Roy Matt. Jan 2020.

SOILLESS GREENHOUSES

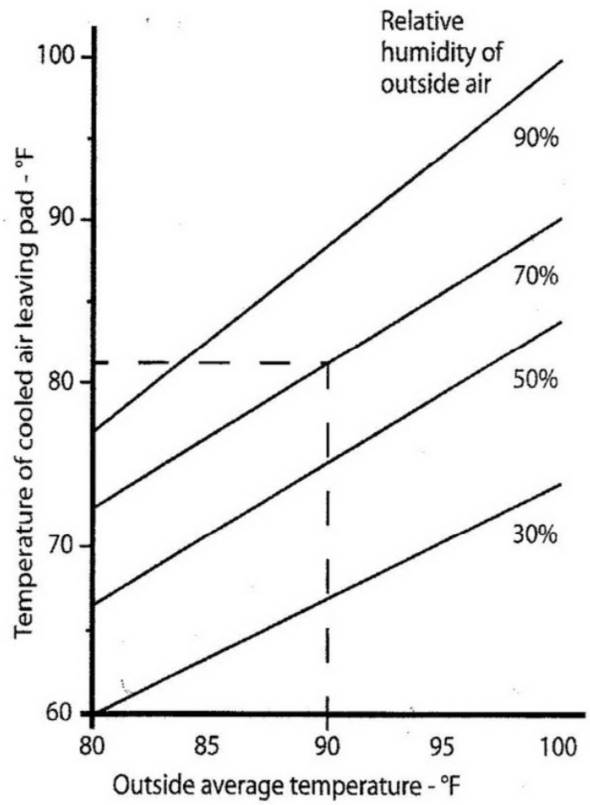
There are already some soilless greenhouses operating in and around St. Louis, but most are still quite small and face many hurdles due to St. Louis' climate. In particular, St. Louis' extreme heat, high humidity, and frequent storms provide difficulties for "traditional" use of greenhouses on local farms.

At one end of the greenhouse spectrum, Good Life Growing operates aquaponic, hydroponic, aeroponic, and other greenhouses to grow food in North St. Louis. They have been using hoop houses, one of the cheapest but least secure forms of greenhouse. Hoop houses provide limited control of the environment but are quick to put up and can be fully vented by hand during the summer. Unfortunately, they are also vulnerable to severe weather. Last year, a nearby tornado destroyed the hoop house covering their aquaponic system.

Hamilton Hospitality, a local restaurant group, has gone one step further in their greenhouse design. They built a permanent greenhouse structure, which is more secure, but with very little technology. They are using 61 aeroponic Tower Gardens inside the greenhouse. These low-pressure aeroponic systems use pumps to mist the roots of plants that grow inside the vertical towers. However, the greenhouses are low tech with no good way to control heat other than vents or setting up large fans. During the summer months, temperatures inside the greenhouse will regularly exceed 100˚F, which is far too hot for the leafy greens inside. While greenhouses' ability to trap heat is helpful in the winter, it is a serious issue during a St. Louis summer. Unfortunately, evaporative cooling, one of the most common cooling methods where air is passed over wet pads, is of little use in St. Louis due to the high humidity. As a result, Hamilton Hospitality can produce during the off-season, but with little ability to grow leafy greens during the summer.

Finally, Ritter Greenhouse operates at the other end of the spectrum. This wholesale grower has been operating in the area since 1966. They have historically focused on non-edible plants, but recently began to grow produce in soilless systems. They converted an existing greenhouse to grow hydroponic basil, which included adding high-pressure sodium lighting to supplement the sunlight, as well as furnaces, water heaters, and a propagation room with LED lighting. Increasing their use of technology allows the farm to produce more, but with higher costs. Basil provides a higher price point than romaine lettuce, making this investment worthwhile, but the trade-offs may vary depending on the hurdles and opportunities with each crop and across each season.

EVAPORATIVE COOLING IS MOSTLY EFFECTIVE IN LOW HUMIDITY CLIMATES.



Efffect of relative humidity of outside air on evaporative cooling

Source: University of Massachusetts Amherst "Fan and Pad Evaporative Cooling Systems"

There are also greenhouses growing produce in soilless conditions in cooler climates (Ohio, Michigan, and Chicago) and drier climates (Arizona) that sell to some St. Louis stores. While they need to ship long distances, the cooler or drier climates are more suited to some greenhouse operations.

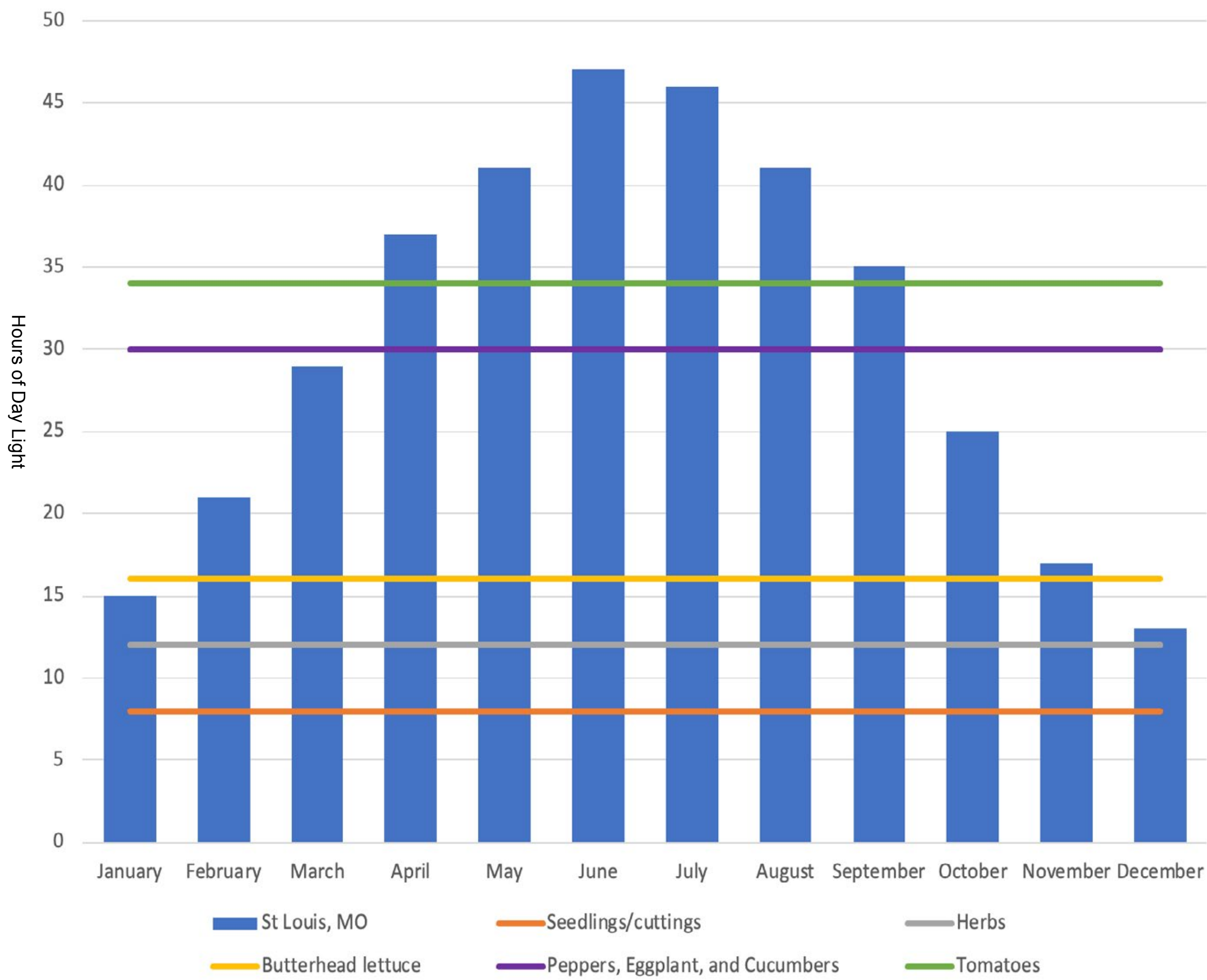
VERTICAL FARMS

There are currently three small-scale vertical farms operating in St. Louis. All of them are housed in the Greencubator, an incubator focused on food start-ups, which is run by Justine PETERSEN, a local nonprofit leader and small business microlender.

Good Life Growing is using a hydroponic, vertical system and focuses on employing recently incarcerated individuals or those transitioning out of homelessness. St. Louis Indoor Produce (SLIP) is also growing hydroponically, but specifically focusing on basil in a tower system. They developed their own lights and are selling those as well. Finally, Urban Space Farms LLC is not running as a profitable farm but is instead focused on creating or incubating the next generation of indoor farming technologies.

Straw Hat Aquaponics, another small-scale vertical farm, used to operate in a former restaurant basement in downtown Ferguson, Missouri but had to shut down in 2019 when the property was sold. They were selling to high-end restaurants and found that most of their revenue came from pea sprouts and microgreens. These products grow extremely quickly and have a very short shelf life, making it hard to ship them.

ST. LOUIS AVERAGE DAY LIGHT INTEGRAL COMPARED TO CROP REQUIREMENT



Source: Ledtonic.com "DLI Chart" and University of Tennessee "US DLI Map"

LAND AND POLICY

St. Louis has myriad spaces that might be suitable for indoor, soilless farming with various policies that might incentivize those locations. This includes abandoned land, brownfield sites, opportunity zones, caves, co-location with power plants, and agriculture support.

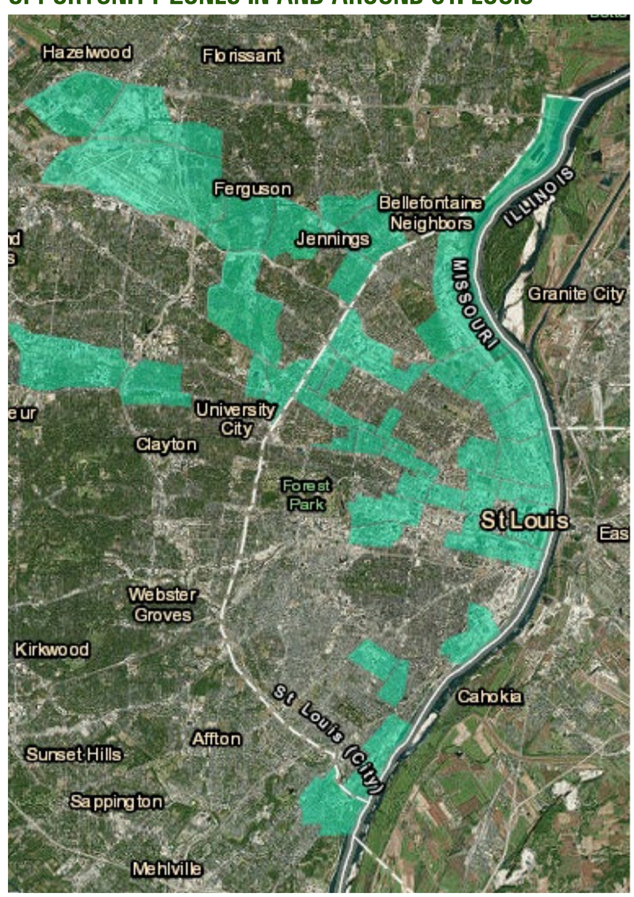
There is currently a significant amount of available property in the city and the county which might be suitable for development of an indoor farming facility. Of the 129,000 total properties in the city of St. Louis, approximately 25,000 are considered vacant and abandoned. About 11,500 of these are owned by the city and might be available through the Land Reutilization Authority (LRA), which comes with a variety of incentives. For example, the Mow to Own program allows commercial property owners to acquire adjacent LRA properties to expand their operations. The Garden Lease program allows residents to lease LRA lots for $1 annually for up to five years to encourage the creation of gardens.

Brownfield sites provide another opportunity. These are sites that were typically contaminated due to industrial operations but might be suitable for indoor farms that require no arable land. Since most brownfield sites previously housed industrial operations, most already have significant access to the electrical grid and other infrastructure. They also come with policy incentives. The Department of Economic Development issues tax credits of up to 100% of the remediation cost of project property. This may include costs of demolition that are not directly part of the remediation activities or on adjacent abandoned properties if the demolition is necessary to accomplish the planned use of the facility.[51]

Opportunity Zones bring another opportunity for tax credits. These are low-income census tracts into which investors can now put capital to work financing new projects and enterprises in exchange for certain federal capital gains tax advantages. The city of St. Louis has 27 designated tracts and there are more in the surrounding county. These tracts are organized into ten clusters that are meant to connect priority areas for investment and span the city's northern, southeastern, and central corridors. The Old North St. Louis and Riverfront cluster is of interest given its approximately 2,000 vacant buildings and lots which are well-suited for industrial development. These include large tracts with rail yards and shipping facilities, as well as brownfield sites.[52]

In addition to other considerations, St. Louis has gas, petroleum, ethanol, and solar power plants in the greater region. Most, but not all, of these are located along the Mississippi River. Since energy is one of the biggest hurdles facing these farms and many of these power plants are under-utilized assets with excess capacity, co-locating may be a good option. Not only could this lower costs for the farms and be energy efficient, but it is possible that the excess heat produced by these farms could be used for further power. Many of the sites around these power plants are also brownfields. This would be a way for energy generation facilities to "green" their offering in the market.

OPPORTUNITY ZONES IN AND AROUND ST. LOUIS



Source: Ridgehouse Capital "Federal Opportunity Zones.

51 Lafser & Associates. *Missouri Brownfield Tax Credits.* 2019. Retrieved November 18, 2019, from http://lafser.com/missouri-brownfield-tax-credits/.

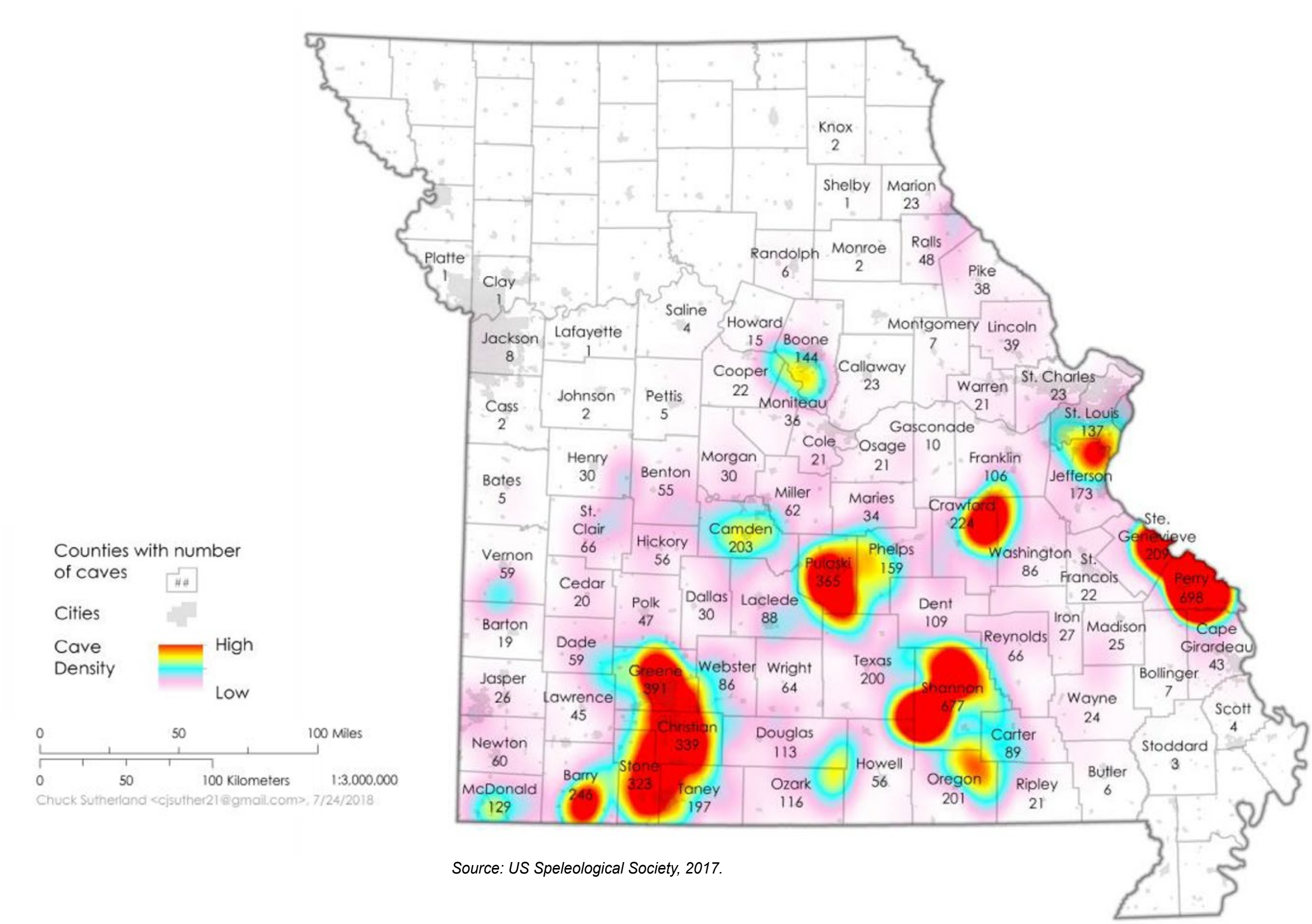
52 *City of St. Louis Opportunity Zone Prospectus Gateway to Opportunity.* St. Louis Development Corporation: November 18, 2019. Retrieved from https://www.stlouis-mo.gov/government/departments/sldc/news/st-louis-releases-opportunity-zone-prospectus-for-developers-and-investors.cfm

Missouri also has more caves than any other state. St. Louis itself is built on a network of caves, some natural and some human-made.[53] Many were used in the past for producing or storing beer, but this ended with the advent of refrigeration in brewing plants. Today, it is estimated that there are 137 caves in the county.[54] Many of these could be useful for farming – especially ones that were previously used in industry.

Finally, there are grants to support agriculture at all government levels. At the federal level, the USDA Specialty Crop Block Grants are meant to enhance the competitiveness of specialty crops. They are distributed through the Missouri Department of Agriculture. While the primary purpose is research, there may be a role here to develop a new industry. In addition, the Agriculture and Food Research Initiative supports six priority areas to advance knowledge that is important to agriculture. Up to $500,000 can be awarded to programs if they develop foundational knowledge of agricultural production systems. In 2018, this specifically included research about protected systems such as hydroponics, aquaponics, aeroponics, vertical farming, and other controlled environment agricultural systems.[55]

Local support and policies can also change frequently. As the industry continues to attract interest and investment, new opportunities may develop, but others may be lost.

ST. LOUIS HAS AN ESTIMATED 137 CAVES



Source: US Speleological Society, 2017.

53 Nunes, Bill. *Caves dominate underground in St. Louis.* St. Louis Post Dispatch, Jan 10, 2008.

54 Missouri Speleological Survey: 2017.

55 *Agriculture and Food Research Initiative Competitive Grants Program.* United States Department of Agriculture, National Institute for Food and Agriculture: 2018. Retrieved November 18, 2019, from https://nifa.usda.gov/sites/default/files/grant/FY%202018_AFRI%20-Foundational_RFA_modified.pdf

NEXT STEPS

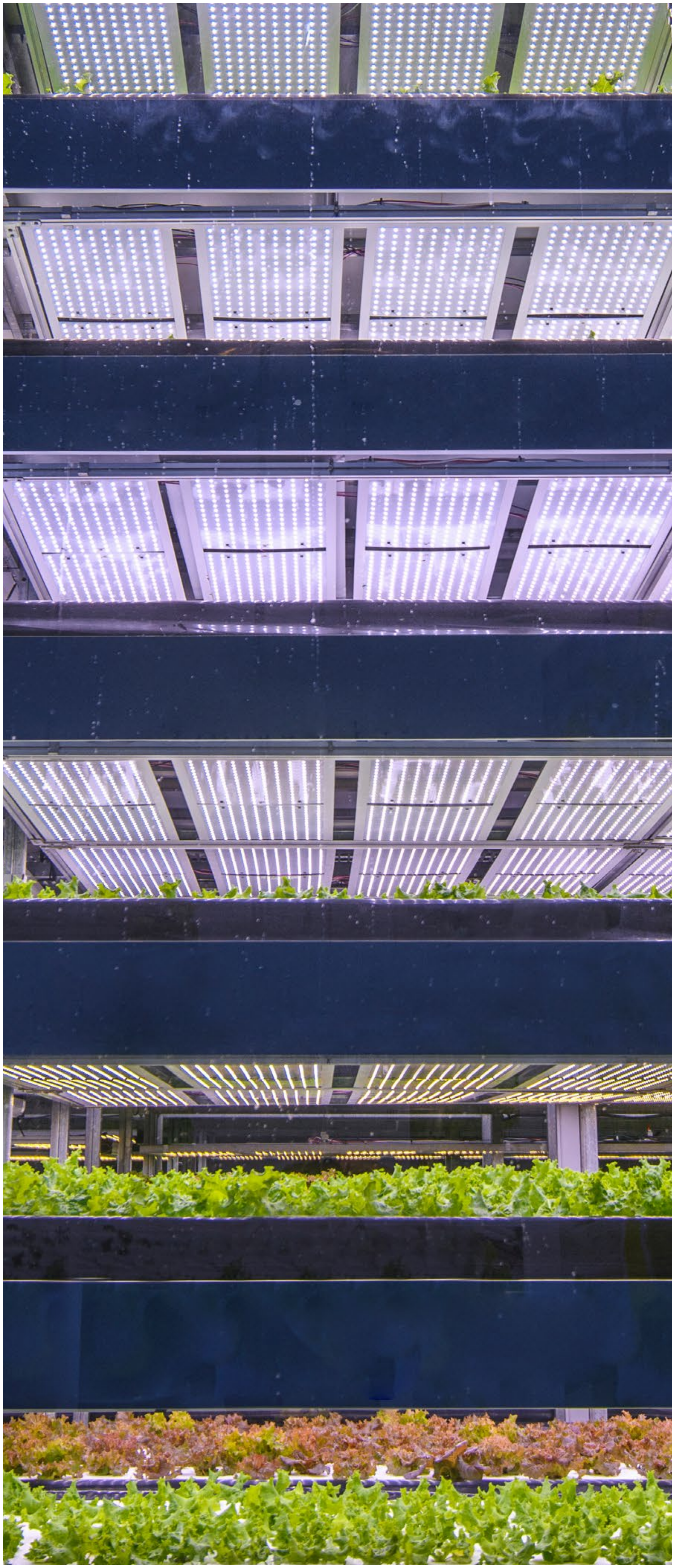
In 2020, we are kicking off the Stakeholder Working Group and, ideally, beginning the design of a pilot that will serve as a test case to see if there is a financially feasible way to scale the industry. We have identified several systems and partnerships that are worth exploring in St. Louis and believe that one of them will be chosen as a viable concept so we can move forward with a dynamic roadmap and a credible business plan. It is also possible that the system chosen could be the first step in a modular approach that shifts as we learn more and continue to find ways to drive costs down. By working as a group to make those decisions, when this project ends, key players will already be invested and ready to move ahead with building a pilot system that can be replicated worldwide, making food production more environmentally sustainable.

APPENDIX I

Comparing the Environmental Impacts of Four Controlled Environment Agriculture Systems with Conventional Agriculture: A Life-Cycle Analysis

Taryn Skinner and Jon Schroeder

WWF



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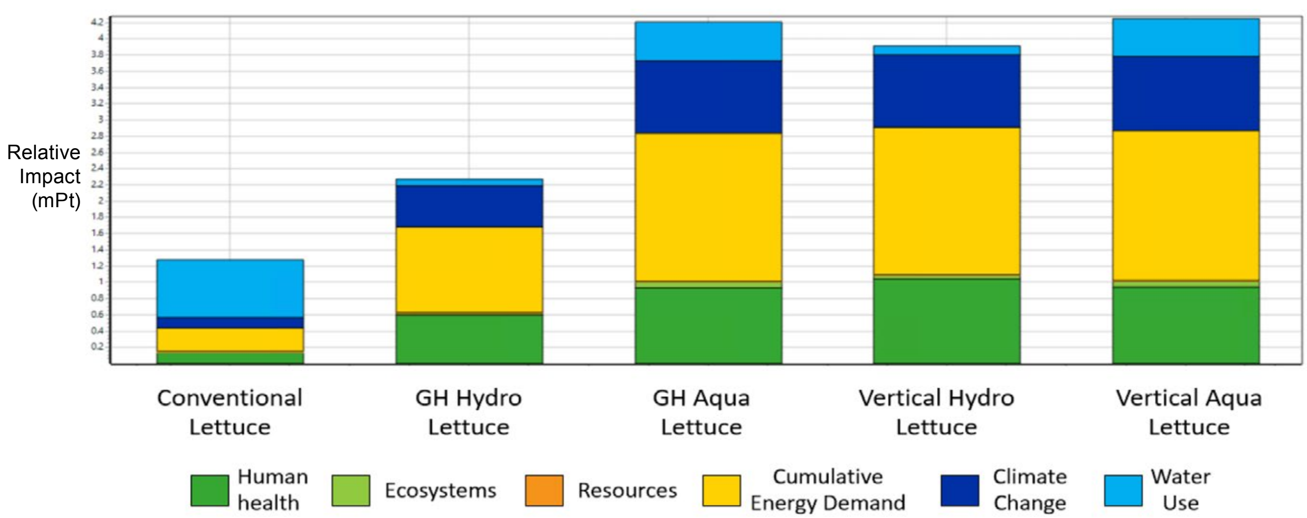
EXECUTIVE SUMMARY

Climate change-related extreme weather events like drought, flooding, and extreme heat are a significant threat to global agricultural productivity.[1] U.S. specialty crop production like fresh vegetables, primarily based in California, is particularly vulnerable to climate change over the next few decades.[2] Controlled environment agriculture (CEA) like greenhouse and vertical systems could potentially make food systems more resilient to climate change by protecting them from extreme weather.[3] CEA systems also could be a valuable tool to address nutritional insecurity in cities because of their year-round production and ability to operate in urban areas.[4]

The purpose of this Life Cycle Assessment (LCA) is to quantify the total environmental impacts of CEA and conventional agriculture to determine which production system is more environmentally sustainable. This LCA compares the environmental impacts of four types of indoor agriculture systems, which are combinations of two different production methods and two different growing environments, and conventional agriculture to produce one kg of romaine lettuce, which is packaged and transported to a grocery store in St. Louis.

Using a single-score comparison with six grouped themes of impact areas to compare the five agricultural systems, our results show that conventionally grown lettuce produced in California and transported to St. Louis has the overall lowest environmental impacts [FIGURE 1]. After conventional lettuce, greenhouse hydroponic lettuce grown in St. Louis and distributed locally has the next lowest amount of environmental impacts. There were three main impact areas that WWF identified as important in the beginning of the study: contribution to climate change, land-use, and water use. In these three categories, conventional agriculture has the lowest impacts associated with climate change [FIGURE 9], primarily because of its lower electricity footprint and cleaner mix of electricity [FIGURE 8]. However, greenhouse hydroponic agriculture received the lowest scores for land use [FIGURE 11] and water use [FIGURE 12] with vertical hydroponics in second, and then conventional agriculture. It is important to note that this does not include an analysis of larger indirect environmental consequences, such as damage caused by dams.

FIGURE 1 COMPARATIVE IMPACT ASSESSMENT OF 18 IMPACT AREAS GROUPED INTO SIX THEMES



1 Lesk, C., Rowhani, P., & Ramankutty, N. (2016). *Influence of extreme weather disasters on global crop production.* Nature, 529(7584), 84. Retrieved from https://www.nature.com/articles/nature16467.

2 Pathak, T. B., Maskey, M. L., Dahlberg, J. A., Kearns, F., Bali, K. M., & Zaccaria, D. (2018). *Climate change trends and impacts on California agriculture: a detailed review.* Agronomy, 8(3), 25. Retrieved from https://www.mdpi.com/2073-4395/8/3/25/pdf.

3 Benke, K & Tomkins, B. (2017). *Future Food-Production Systems: Vertical Farming and Controlled environment Agriculture*. Sustainability: Science, Practice and Policy. 13:1, 13-26, DOI: 10.1080/15487733.2017.1394054.

4 Thomaier, S., Specht, K., Henckel, D., Dierich, A., Siebert, R., Freisinger, U. B., & Sawicka, M. (2015). *Farming in and on urban buildings: Present practice and specific novelties of Zero-Acreage Farming (ZFarming)*. Renewable Agriculture and Food Systems, 30(1), 43-54. Retrieved from https://www.cambridge.org/core/journals/renewable-agriculture-and-food-systems/article/farming-in-and-on-urban-buildings-present-practice-and-specific-novelties-of-zeroacreage-farming-zfarming/B1B85E6F51C51DBF134879F8C7565461.

Of the other impact areas, the four controlled environment agriculture systems all had higher impacts on human health and ecosystems relative to conventional agriculture [FIGURE 1]. The primary driver of the impacts to these two categories stem from the systems' different electricity usage and grid mixes. In addition to higher GHG emissions per kwh, the St. Louis electricity grid has higher ecosystem and human toxicity level impacts than California electricity.[5]

The two aquaponics systems show much higher environmental impacts than the other three systems [FIGURE 1]. We allocated the environmental impacts based on the relative economic value of production and calculated an allocation of 75% of impacts going to lettuce and 25% of impacts going to tilapia. The main drivers for the environmental impacts in aquaponics, apart from electricity, come from tilapia feed, which particularly contributes to land and water use [FIGURE 13].

Of the two hydroponics systems, greenhouse hydroponic lettuce has a significantly lower footprint than vertical hydroponic lettuce across all six thematic groups [FIGURE 15]. The main driver of this difference is vertical agriculture's higher electricity use due to using LED lights as its primary source of plant light.

One reason that the four CEA systems had higher environmental impacts than conventional agriculture [FIGURE 1] is because of CEA agriculture's higher electricity use. We modeled a hypothetical scenario where the electricity use for all five systems is sourced from U.S. photovoltaic solar power instead of the standard regionally specific mixes [FIGURE 17]. In this model, greenhouse and vertical hydroponic systems have overall lower environmental impacts than conventional agriculture, with drastically lower level impacts on human and ecosystem health. This suggests that either hydroponics systems would be a more environmentally sustainable choice than conventionally grown lettuce if the farm is able to directly source solar electricity, or else pay to receive solar credits.

With current technology efficiency, electricity sources, and natural resource availability, conventional agriculture has the lowest total environmental impacts of the five agricultural systems that we modeled. Further, if hydroponics farms source their electricity from renewable energy like solar, or wind which is increasingly available in Missouri, instead of the standard regional mix used by St. Louis, then both greenhouse and vertical hydroponics farms would have lower environmental impacts than conventional agriculture. Another possible option is to make use of St. Louis's stranded assets by partnering with electricity plants to use surplus energy during certain times of day allowing the plants to produce energy more uniformly and therefore more efficiently.

Out of the indoor, soilless options, a greenhouse hydroponics farm would be the most environmentally sustainable choice for the St. Louis region for the foreseeable future, until LED technology can make significant enough efficiency gains to reduce the energy footprint of vertical agriculture. Situating the greenhouse on otherwise unused space like a building roof could further reduce the environmental impacts of greenhouse hydroponic agriculture by reducing its land-use footprint.

5 EcoInvent (2018). *The Ecoinvent Database Version 3*. The International Journal of Life Cycle Assessment 1(9). Accessed via SimaPro.

INTRODUCTION

Climate change-related extreme weather events like drought, flooding, and extreme heat are a significant threat to global agricultural productivity.[6] U.S. specialty crop production like fresh vegetables, primarily based in California, is particularly vulnerable to climate change over the next few decades.[7] Controlled environment agriculture (CEA) like greenhouse and vertical systems could potentially make food systems more resilient to climate change by protecting them from extreme weather.[8] CEA agriculture also has the potential to reduce pressure on natural habitats by reducing the amount of land required for farming through higher production per square foot. Although still a niche form of food production, the CEA market is rapidly growing and reached $21 billion in 2018.[9] CEA systems also could be a valuable tool to address nutritional insecurity in cities because of their year-round production and ability to operate in urban areas.[10]

Despite the potential of these systems to help achieve positive environmental and social outcomes, they also come with drawbacks like higher energy requirements relative to conventional agriculture.[11] The purpose of this Life Cycle Assessment (LCA) is to quantify the total environmental impacts of CEA and conventional agriculture to determine which production system is more environmentally sustainable. This LCA compares the environmental impacts of four types of indoor agriculture systems, which are combinations of two different production methods and two different growing environments, and conventional agriculture to produce one kg of lettuce, which is packaged and transported to a grocery store in St. Louis. It looks at the different food production systems solely through the lens of environmental impacts and does not take into account other factors like social and economic impacts. The two controlled environment agriculture production methods we analyzed are hydroponic and aquaponic systems. The two production conditions we analyzed are greenhouse and vertical agriculture.

6 Lesk, C., Rowhani, P., & Ramankutty, N. (2016). *Influence of extreme weather disasters on global crop production.* Nature, 529(7584), 84. Retrieved from https://www.nature.com/articles/nature16467.

7 Pathak, T. B., Maskey, M. L., Dahlberg, J. A., Kearns, F., Bali, K. M., & Zaccaria, D. (2018). *Climate change trends and impacts on California agriculture: a detailed review.* Agronomy, 8(3), 25. Retrieved from https://www.mdpi.com/2073-4395/8/3/25/pdf.

8 Benke, K & Tomkins, B. (2017). *Future Food-Production Systems: Vertical Farming and Controlled environment Agriculture*. Sustainability: Science, Practice and Policy. 13:1, 13-26, DOI: 10.1080/15487733.2017.1394054.

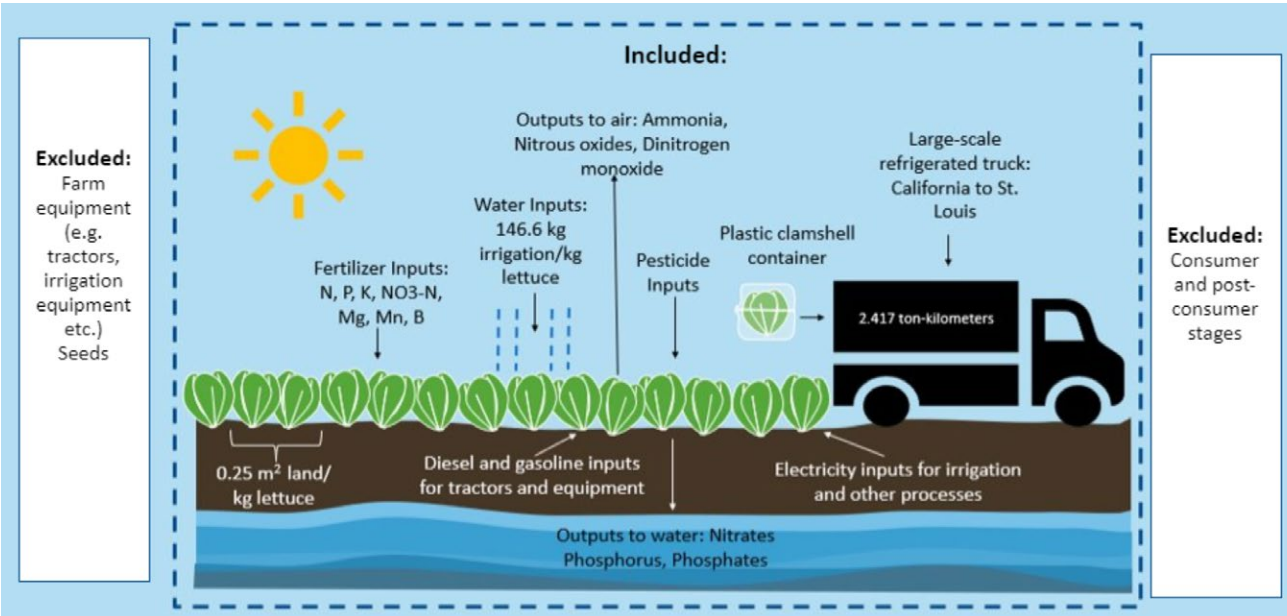
9 Fast.MR (2018). *Controlled Environment Agriculture Market.* Market Research Report. Retrieved from https://www.fastmr.com/report/2/controlled environment-agriculture-market.

10 Thomaier, S., Specht, K., Henckel, D., Dierich, A., Siebert, R., Freisinger, U. B., & Sawicka, M. (2015). *Farming in and on urban buildings: Present practice and specific novelties of Zero-Acreage Farming (ZFarming)*. Renewable Agriculture and Food Systems, 30(1), 43-54. Retrieved from https://www.cambridge.org/core/journals/renewable-agriculture-and-food-systems/article/farming-in-and-on-urban-buildings-present-practice-and-specific-novelties-of-zeroacreage-farming-zfarming/B1B85E6F51C51DBF134879F8C7565461.

11 Barbosa, G., Gadelha, F., Kublik, N., Proctor, A., Reichelm, L., Weissinger, E., ... & Halden, R. (2015). *Comparison of land, water, and energy requirements of lettuce grown using hydroponic vs. conventional agricultural methods.* International journal of environmental research and public health, 12(6), 68796891. Retrieved from https://www.mdpi.com/1660-4601/12/6/6879/pdf.

SYSTEM 1: CONVENTIONAL AGRICULTURE

FIGURE 2 SYSTEM BOUNDARIES DIAGRAM OF THE CONVENTIONAL AGRICULTURE SYSTEM

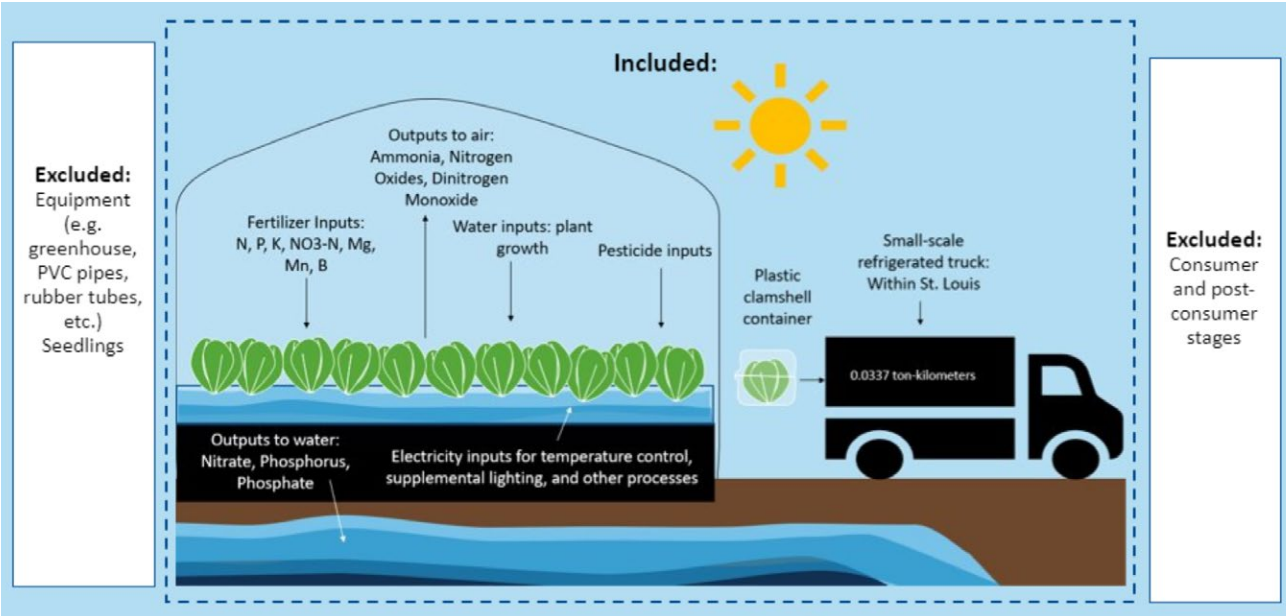


For the conventional agriculture LCA, we assumed that lettuce production would occur in Monterey County, California. We chose this region because California is the leading producer of lettuce in the U.S., and Monterey County produces 57% of California's lettuce production.[12] For the conventional agriculture system, we modeled a system based on our life-cycle inventory (see Life Cycle Inventory) that grows lettuce in soil with inputs of inorganic fertilizer, pesticides, and water, and outputs of air and water pollution [FIGURE 2]. This system uses heavy farm machinery powered by gasoline and diesel fuel and transports the lettuce to St. Louis in a large refrigerated truck. We excluded permanent farm equipment like tractors from the study but included the impacts from the fuel and combustion process of these machines. We also excluded any impacts at the consumer and post-consumer stages in all of the systems.

12 Geisseler, D. & Horwath, W. (2016). *Lettuce Production in California*. Assessment of Plant Fertility and Fertilizer Requirements for Agricultural Crops in California. University of California, Davis. Retrieved from https://apps1.cdfa.ca.gov/FertilizerResearch/docs/Lettuce_Production_CA.pdf.

SYSTEM 2: GREENHOUSE HYDROPONICS AGRICULTURE

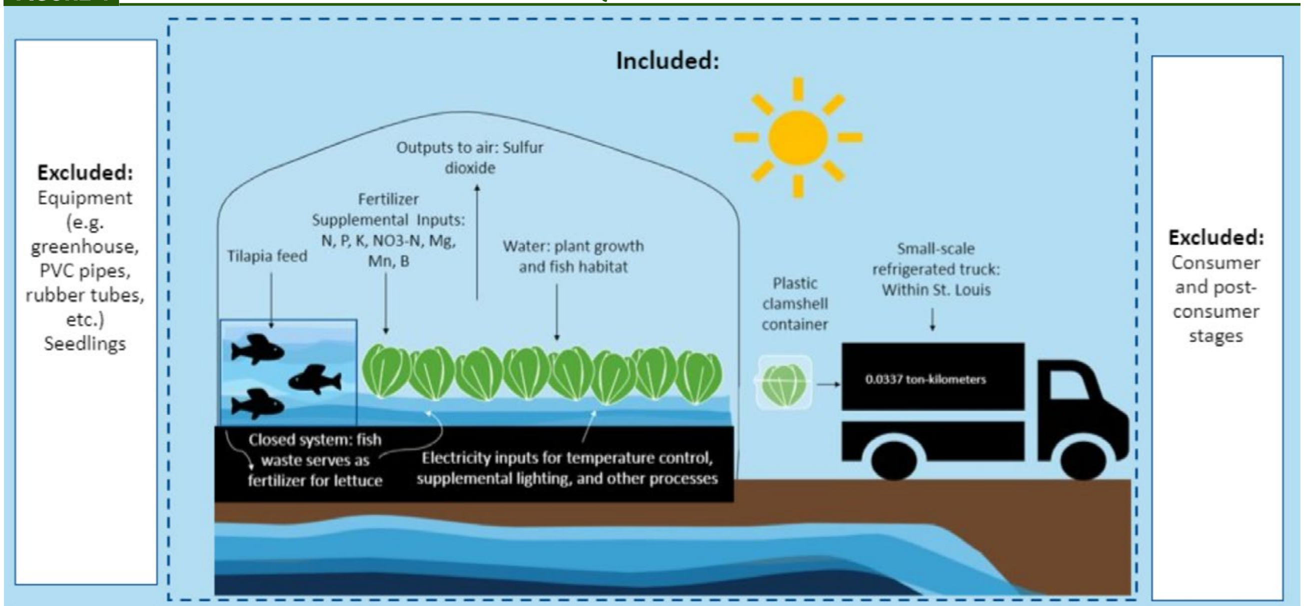
FIGURE 3 SYSTEM BOUNDARIES DIAGRAM OF THE GREENHOUSE HYDROPONICS SYSTEM



The greenhouse hydroponic system that we modeled based on the data we collected in our life cycle inventory (see Life Cycle Inventory section) included a transparent glass exterior and lettuce in a soilless, nutrient-rich solution with inputs from water, inorganic fertilizers, and pesticides. It produced air and water pollution as outputs. This system used sunlight as its primary light source for plants, with some supplemental LED lighting. We assumed that the four soilless systems all were situated within the city of St. Louis and transported an average of 21 miles in a small refrigerated truck. We excluded permanent equipment for this system like the greenhouse itself, pipes, etc. but did include the electricity required to power the greenhouse.

SYSTEM 3: GREENHOUSE AQUAPONICS AGRICULTURE

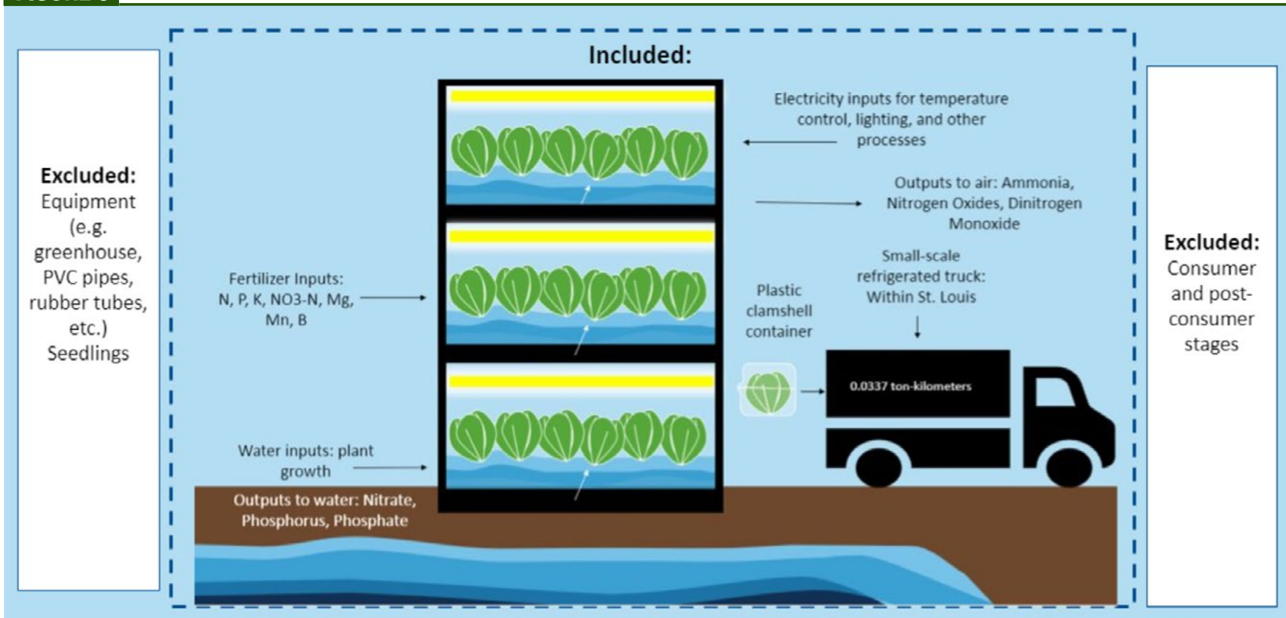
FIGURE 4 SYSTEM BOUNDARIES DIAGRAM OF THE GREENHOUSE AQUAPONICS SYSTEM



The greenhouse hydroponic system that we modeled based on the data we collected in our life cycle inventory (see Life Cycle Inventory section) included a transparent glass exterior and lettuce in a soilless solution with tilapia as a coproduct. Aquaponic agriculture grows crops in a recirculating system; waste emissions from the fish provide fertilizer. This system's inputs included supplemental inorganic fertilizer, tilapia fingerlings, tilapia feed, and water; its outputs include water pollution. The greenhouse system used sunlight as its primary light source for plants, with some supplemental LED lighting. We assumed that the four soilless systems all were situated within the city of St. Louis and transported an average of 21 miles in a small refrigerated truck. We excluded permanent equipment for this system like the greenhouse itself, pipes, etc. but did include the electricity required to power the greenhouse.

SYSTEM 4: VERTICAL HYDROPONICS AGRICULTURE

FIGURE 5 SYSTEM BOUNDARIES DIAGRAM OF THE VERTICAL HYDROPONICS SYSTEM

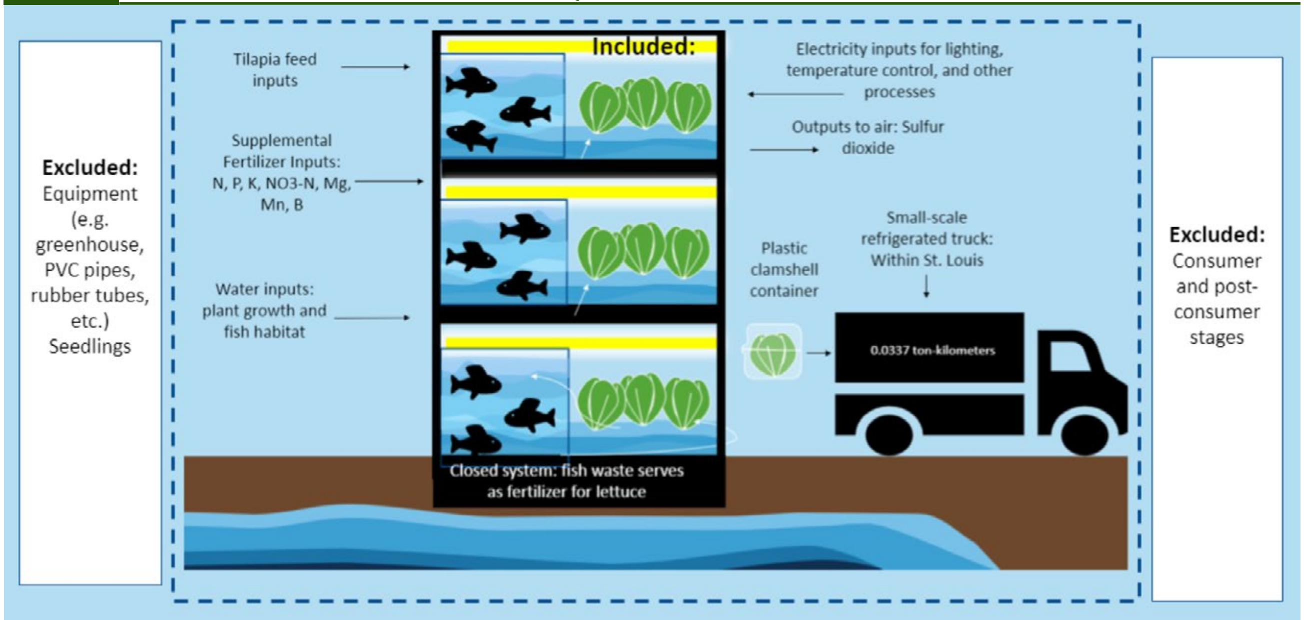


The vertical hydroponic system that we modeled based on the data we collected in our life cycle inventory (see Life Cycle Inventory section) included a building with opaque walls and lettuce in a soilless, nutrient-rich solution with inputs from water and inorganic fertilizers. We did not include pesticides in this system as the leading vertical farms in the U.S. state that they are pesticide-free.[13] It produced air and water pollution as outputs. This system's primary source of lighting from crops is LED lightbulbs. We assumed that the four soilless systems all were situated within the city of St. Louis and transported an average of 21 miles in a small refrigerated truck. We excluded permanent equipment for this system like the building, lightbulbs, pipes, etc. but did include the electricity required to power the growing system.

13 AeroFarms (n.d.) Home. Retrieved from https://aerofarms.com/.

SYSTEM 5: VERTICAL AQUAPONICS AGRICULTURE

FIGURE 6 SYSTEM BOUNDARIES DIAGRAM OF THE VERTICAL AQUAPONICS SYSTEM



The vertical aquaponic system that we modeled based on the data we collected in our life cycle inventory (see Life Cycle Inventory section) included a building with opaque walls and lettuce in a soilless, nutrient-rich solution with tilapia as a coproduct. Aquaponic agriculture grows crops in a recirculating system; waste emissions from the fish provide fertilizer. This system's inputs included supplemental inorganic fertilizer, tilapia fingerlings, tilapia feed, and water; its outputs include water pollution. Its primary source of lighting from crops is LED lightbulbs. We assumed that the four soilless systems all were situated within the city of St. Louis and transported an average of 21 miles in a small refrigerated truck. We excluded permanent equipment for this system like the building, lightbulbs, pipes, etc. but did include the electricity required to power the growing system.

13 AeroFarms (n.d.) Home. Retrieved from https://aerofarms.com/.

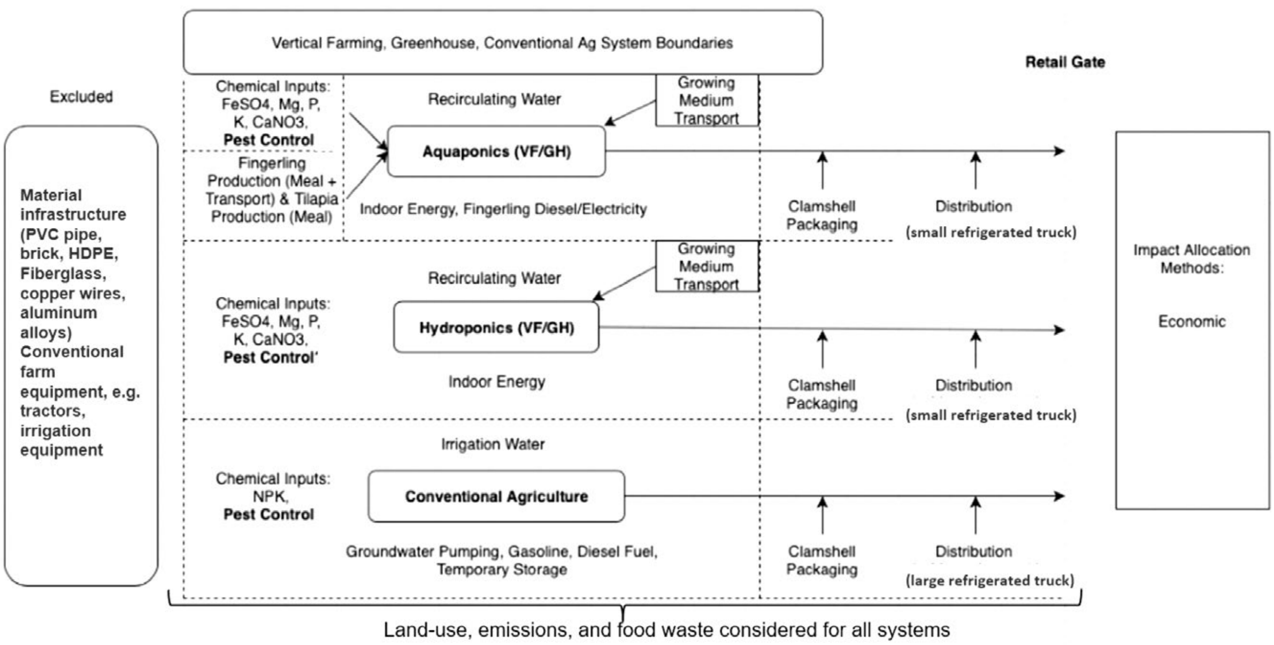
METHODS

GOAL AND SCOPE

The goal of this study was to compare the environmental impacts of greenhouse and vertical hydroponic and aquaponic systems, both between each other and with conventional agriculture. Because of this, the study drew its system boundaries to exclude components of the product's life that are universal to all systems. These include lettuce seeds, consumer use, and post-consumer waste. This study will be used to inform the internal decision-making process for a WWF project designing a controlled environment system in the St. Louis region. Where relevant, this study used St. Louis-specific data, such as estimating transportation distances and waste disposal.

The system boundaries of the LCA are included in the diagram below:

FIGURE 7 A COMPLETE DIAGRAM OF THE SYSTEMS' BOUNDARIES



FUNCTIONAL UNIT

A functional unit is a standardized output to allow the comparison of different systems. For this study we chose one kilogram (kg, approximately 2.205 pounds) of lettuce which has been packaged and transported to the grocery store as our functional unit of comparison. CEA systems have the potential to grow a variety of different crops, from leafy greens to fruiting produce like tomatoes and bell peppers.[14] We selected lettuce as the crop to use as our functional unit of comparison because it is the most popular crop for vertical farms, with leafy greens representing 57% of total global vertical agriculture production.[15]

We chose to make the functional unit 1 kg of lettuce which has been produced, packaged, and transported from point-of-origin to a grocery store in St. Louis. Adding distribution allowed us to capture the differences in environmental impacts from conventional agriculture, where transportation would be more efficient per-kg-per-km but a longer distance, with the four soilless systems which will be local to St. Louis but less efficient per-kg-per-mile due to smaller delivery loads.

ALLOCATION

Two of the systems that we analyzed, Greenhouse Aquaponic and Vertical Aquaponic, produce two food products: lettuce and tilapia. To accurately account for the environmental impacts of these systems using the functional unit of 1 kg of lettuce, we allocated impacts of these systems between the lettuce and tilapia by the mass and economic value of their production. An aquaponic system typically produces a ratio of X lettuce to Y tilapia by mass. To calculate the economic value of each, we used retail prices for lettuce in the St. Louis region, and live-weight tilapia from a U.S. grocery store. We chose live-weight tilapia to simplify the system and omit potential complexities from butchering fish, like additional transportation and energy.

LIFE CYCLE INVENTORY | NUTRIENT COMPOSITION

There were five core nutrients that were modeled for both the aquaponic and hydroponic systems. According to an optimal solution proposed by Delaide et al. 2016,[16] a ratio was established for modeling purposes to achieve optimal solution per kg-lettuce. This ratio was needed because the water estimates coming from different journal articles were varied, and the optimal ratios are given in mg/L. Thus, you would need to know the actual amount of water in a system to establish an amount of solution.

The beginning value for nutrient amount was taken from a study,[17] in which multiple values were given for hydroponic systems. Potassium was used as the origin value upon which every other value was calculated. As a reference, these values were compared against conventional agriculture values in SimaPro and a study by Emery and Brown 2016;[18] the magnitude appeared to be similar. Nutrient usage between a vertical farm and greenhouse within each growing system was assumed to be similar for modeling purposes.

Conventional agriculture solution NPK values were taken from Emery and Brown 2016, and remaining values were calculated according to ratios given in Tamura et al. 2018. In addition to NPK, Boron, Magnesium, Manganese, and NO3-N were modeled.

TABLE 1 OPTIMAL NUTRIENT SOLUTIONS (KG, PER KG OF LETTUCE)

kg/kg lettuce	Aqua GH	Aqua VF	Hydro GH	Hydro VF	Conventional
Magnesium Oxide			6.86E-04		
Iron Sulfate	3.89E-04		2.02E-03		
Calcium Nitrate	2.04E-04		6.69E-03		
Potassium Sulfate	7.68E-04		3.60E-03		1.49E-03
Phosphorus Trichloride	2.1156E-04		8.57E-04		5.29E-04
Nitrogen			2.67E-05		4.4E-03
Magnesium Sulfate	1.01E-03				
Multi-micronutrient base fertilizer					9.6E-03

Sources: Emery & Brown (2016); Romeo et al. (2015); Graamans et al. (2018)

14 Al-Kodmany, K. (2018). *The vertical farm: A review of developments and implications for the vertical city.* Buildings, 8(2), 24.Retrieved from https://www.mdpi.com/2075-5309/8/2/24/pdf.

15 Agrilyst (2017). *State of Indoor Farming*. Retrieved from https://artemisag.com/wpcontent/uploads/2019/06/stateofindoorfarming-report-2017.pdf.

16 Delaide, B., Goddek, S., Gott, J., Soyeurt, H., & Jijakli, M. H. (2016). Lettuce (Lactuca sativa L. var. Sucrine). *Growth performance in complemented aquaponic solution outperforms hydroponics.* Water, 8(10), 467. Retrieved from https://www.mdpi.com/2073-4441/8/10/467.

17 Romeo, D., Vea, E. B., & Thomsen, M. (2018). *Environmental impacts of urban hydroponics in Europe: a case study in Lyon.* Procedia CIRP, 69, 540-545. Retrieved from https://www.sciencedirect.com/science/article/pii/S221282711730820X/pdf?md5=d2bc16bf82db786dcc9b2ffe0033&pid=1-s2.0-S221282711730820X-main.pdf.

18 Emery, I., & Brown, S. (2016). *Lettuce to Reduce Greenhouse Gases: A Comparative Life Cycle Assessment of Conventional and Community Agriculture.* In Sowing Seeds in the City (pp. 161-169). Springer, Dordrecht.

LIFE CYCLE INVENTORY | LAND USE

Land use is increasingly becoming an integral part of LCA studies, as practitioners are beginning to understand the carbon fluxes involved with converting certain land types into other land types for food production (example: forests into pasture or crop production). For this LCA, we assumed the lettuce production would take place on existing cropland in California. This means conversion factors didn't need to be considered.

However, the occupation of land needed to grow the functional unit can be modeled. For conventional agriculture, occupational arable land was established at 0.25 m2a (square meter-years).[19] For hydroponic and aquaponic system setups, less land is needed due to growing density, with greenhouse hydroponic production using 0.024 m2a and vertical hydroponic production using 0.01 m2a.[20] We assumed that that greenhouse and vertical aquaponic systems' direct land-use would be similar to the hydroponics systems. Aquaponics systems also have indirect land-use embedded in the tilapia feed inputs in the EcoInvent database.

LIFE CYCLE INVENTORY | ENERGY

Energy was one of the most complex allocation challenges of all components of this study, as it was initially thought energy values could be found for several sub-systems. However, after running some preliminary results for energy use from LCAs, it was evident that relying on individual LCAs for energy information led to highly variable results, as the assessments' system boundaries for sub-systems varied widely. To prevent the potential for skewed results, we used the averages from a combined analysis of several vertical and greenhouse systems in different geographies to produce 1 kg of dry-weight lettuce.[21] We then normalized this for our functional unit with the premise that fresh lettuce is 95% water,[22] and calculated that 0.05 kg of dry-weight lettuce is equivalent to 1 kg of fresh lettuce.

Conventional agriculture energy was modeled for petroleum (0.04 kg) and diesel use (0.44 kg) by farm equipment.[23] Additionally, electricity usage was modeled at 1100 kJ.[24] This value was given in kJ/kg/year in Arizona and was exclusively dedicated to pumping irrigation water. We have assumed that energy needs for lettuce production in Monterey County California would be similar given their comparable climates and water resources.

Greenhouses will typically use energy for recirculating water, aeration diffusers for bacterial mediation of nutrients that plants can absorb, evaporative cooling, and HVAC. Heating and cooling would especially come into the picture in a colder climate like St. Louis, where in the four-season weather model, those energy sources would be needed to help lettuce grow under optimal temperature conditions.

In greenhouses, sunlight accounts for most of the energy required by plants to photosynthesize during the day. In vertical farms, no transparent façade is intact and artificial lighting is exclusively relied on to help plants photosynthesize. Vertical farms typically use electricity like greenhouses, only growing lights (LEDs or other) will be the energy source for the plant to photosynthesize, rather than sunlight. HVAC, aeration diffusers, and circulation pumps would be used similarly to in a greenhouse, only the HVAC needs would stay relatively constant depending on season (greenhouses could fluctuate in HVAC usage daily depending on sunlight and time of day).

In EcoInvent, we selected region-specific electricity mixes to capture the differences in impacts between electricity generated in St. Louis and California. The electricity mix in St. Louis is 32% coal, 35% natural gas, 26% nuclear, 3% hydro, and 2% biomass. The electricity mix in California is 23% coal, 30% natural gas, 8% nuclear, 24% hydro, 1% biomass, 2% geothermal, 4% solar, and 7% wind.[25] These differences mean that a kilowatt of electricity produced in California has a smaller overall environmental impact compared with a kilowatt of electricity produced in St. Louis [FIGURE 8].

21 Graamans, L., Baeza, E., Van Den Dobbelsteen, A., Tsafaras, I., & Stanghellini, C. (2018). *Plant factories versus greenhouses: Comparison of resource use efficiency.* Agricultural Systems, 160, 31-43. Retrieved from https://www.researchgate.net/profile/Esteban_Baeza/publication/321379221_Plant_factories_versus_greenhouses_Comparin_of_resource_use_efficiency/links/5a1fc6f2a6fdccc6b7fb6b48/Plant-factories-versus-greenhouses-Comparison-ofresource-use-efficiency.pdf.

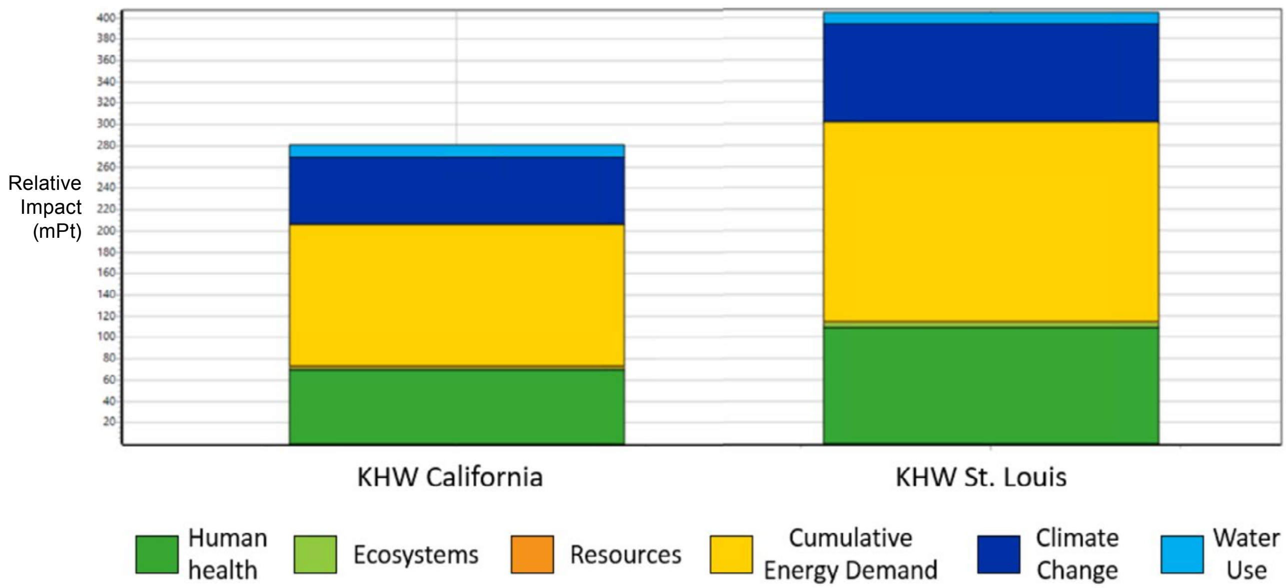
22 Berkeley Wellness (2011). *How Much Water is in Your Food?* University of California. Retrieved from https://www.berkeleywellness.com/healthy-eating/food/article/how-much-water-your-food.

23 Emery, I., & Brown, S. (2016). *Lettuce to Reduce Greenhouse Gases: A Comparative Life Cycle Assessment of Conventional and Community Agriculture.* In Sowing Seeds in the City (pp. 161-169). Springer, Dordrecht.

24 Barbosa, G., Gadelha, F., Kublik, N., Proctor, A., Reichelm, L., Weissinger, E., ... & Halden, R. (2015). *Comparison of land, water, and energy requirements of lettuce grown using hydroponic vs. conventional agricultural methods.* International journal of environmental research and public health, 12(6), 6879 6891. Retrieved from https://www.mdpi.com/1660-4601/12/6/6879/pdf.

25 Long Trail Sustainability (2018). *Datasmart LCI Packaging Manual.* U.S. eGRID Electricity Mixes. Data from EPA (2016). Retrieved from https://ltsexperts.com/wp-content/uploads/2018/12/LTS-DATASMART-LCI-Package-Manual_2018-3.pdf.

FIGURE 8 A SINGLE-SCORE COMPARISON ON THE ENVIRONMENTAL IMPACTS OF 1 KWH IN CALIFORNIA AND ST. LOUIS



LIFE CYCLE INVENTORY | WATER

Recirculating water within Greenhouse hydroponics was modeled at 5.96 kg of water/kg lettuce,[26] and recirculating water within Vertical hydroponics was modeled at 1 L or kg/kg lettuce.[27] Recirculating water within Greenhouse aquaponics and Vertical aquaponics was modeled at 14.66 kg[28] respectively, as it was estimated roughly 10% of conventional water use is needed in a greenhouse setting.[29] Irrigation water in conventional agriculture was modeled at 146.6 L per kg of lettuce.[30]

LIFE CYCLE INVENTORY | PESTICIDE USE

Pesticides were modeled for hydroponics and conventional agriculture. For conventional agriculture, pesticide use was calculated at 2.5E-04 kg/kg lettuce.[31] For Greenhouse hydroponic, pesticides modeled were more specific because of an LCA study and included potassium hydroxide (7.97E-05 kg/kg lettuce), coconut oil (7.97E-05 kg/kg lettuce) and tap water (0.0185 kg/kg lettuce).[32] Vertical hydroponic was assumed to use the same pesticides as Greenhouse hydroponic systems. We did not include pesticide use in either aquaponics system, as pesticides are not commonly used in this type of system[33] and were not used in our primary source of life cycle inventory data for tilapia-lettuce aquaponics.[34] Peat was modeled as a growing medium for seedlings for Greenhouse hydroponics and was assumed to be similar for the other three soilless systems at 3.91E-03 kg/kg lettuce.[35]

26, 32, 35 Romeo, D., Vea, E. B., & Thomsen, M. (2018). *Environmental impacts of urban hydroponics in Europe: a case study in Lyon*. Procedia CIRP, 69, 540-545. Retrieved from https://www.sciencedirect.com/science/article/pii/S221282711730820X/pdf?md5=d2bc16bf82db786dcc9b2ffe0033&pid=1-s2.0-S221282711730820X-main.pdf.

27, 29 Nausm T. (2018). *Is Vertical Farming Really Sustainable?* EIT Food. Plantlab. Retrieved from https://www.eitfood.eu/blog/post/is-vertical-farming-really-sustainable.

28 Cohen, A., Malone, S., Morris, Z., Weissburg, M., & Bras, B. (2018). *Combined Fish and Lettuce Cultivation: An Aquaponics Life Cycle Assessment*. Procedia CIRP, 69, 551-556. Retrieved from https://www.sciencedirect.com/science/article/pii/S2212827117307989/pdf?md5=57b361633a26f2e2ceac2779eff3d74d&pi.0-S2212827117307989-main.pdf.

30 Emery, I., & Brown, S. (2016). *Lettuce to Reduce Greenhouse Gases: A comparative Life Cycle Assessment of Conventional and Community Agriculture*. In Sowing Seeds in the City (pp.161-169). Springer, Dordrecht.

31 Foteinis, S., & Chatzisymeon, E. (2016). *Life cycle assessment of organic versus conventional agriculture. A case study of Lettuce cultivation in Greece*. Journal of cleaner production, 112, 2462-2471. Retrieved from https://pubag.nal.usda.gov/catalog/5652002.

33 Hindelang, M., Gheewala, S. H., Mungkung, R., & Bonnet, S. (2014). Environmental Sustainability Assessment of a Media Based Aquaponics System in Thailand. J. Sustain. Energy Environ., 5, 109-116. Retrieved from http://www.thaiscience.info/Journals/Article/JOSE/10985108.pdf

LIFE CYCLE INVENTORY | FINGERLING/TILAPIA PRODUCTION

We assumed that the two aquaponic farms would source their fingerlings from Overlook Farm, the closest tilapia fingerling producer,[36] which is 121 km from St. Louis, and that fingerling transportation would be via ground transportation in a small refrigerated truck carrying a 1-ton load. We further assumed that the tilapia fingerlings and water for storage required to produce 0.2 kg of tilapia (1 kg of lettuce) would be 0.1 kg; this calculates out to 0.0121 metric-ton-kilometers. For the fingerling inputs, we used data from the Life Cycle Inventory from Cohen et al.'s (2018) LCA on tilapia-lettuce aquaponics and calculated a conversion (Table 2) from their function unit of 1 metric ton of tilapia to our function unit of 0.2 kg of tilapia (1 kg of lettuce). We assumed that greenhouse and vertical systems would have no difference in fingerling to full-grown tilapia ratios.

TABLE 2 FINGERLING/TILAPIA PRODUCTION INPUTS AND FEED PER KG LETTUCE IN AQUAPONIC SYSTEMS (GH AND VF)

Fingerling Inputs (Cohen et al., 2018)	
Mixed fingerling feed	0.1694 kg
Electricity	2.18 mj
Transportation	0.0121 tkm (tonne-kilometre)
Tilapia Feed	
Wheat feed	0.39 kg
Rapeseed Meal	0.11 kg
Fishmeal	0.39 kg
Soybean feed	0.357 kg

LIFE CYCLE INVENTORY | EMISSIONS

Emissions to air and water were modeled for both conventional and hydroponic systems. No soil emissions data was found for conventional agriculture, though engineering estimates or SimaPro estimates for global production could be used to approximate values. However, these soil emissions would most likely only increase the impacts in the areas of Terrestrial Ecotoxicity, Aquatic Ecotoxicity, Marine Ecotoxicity, and Human Toxicity. This is because these four impact categories, depending on the impact calculation method, use similar units.

Pesticides and effluents are not common in aquaponic systems because the setup mimics a natural system in which the cycling of nutrients benefits both the tilapia and lettuce.[37] Effluents from occasional water flushes in the system could arise from fish meal being used to feed tilapia, and the primary study we used for the aquaponics noted sulfur dioxide as an output to water.[38] The impacts of these effluents would be attributed to wastewater treatment, as that is where any nutrient loads would be treated.

Conventional agriculture is also assumed to have a food spoilage rate of 34% pre-retail, with 20% occurring at production level, and 14% occurring between harvest and grocery store (Rezaei & Liu, 2017). Controlled environment agriculture averages 80% less food waste than conventional agriculture during the production stage,[39] so we assumed a 6.8% food waste rate for the four soilless systems.

TABLE 3 EMISSIONS FROM AGRICULTURE SYSTEMS

kg/kg lettuce	Sub compartment		
System	Air	Water	Soil
VF – Hydro (assumed to be like estimates for GH)	Ammonia: 9.44E-05 Nitrogen Oxides: 2.67E-05 Dinitrogen monoxide: 2.67E-05	Nitrate: 5.5E-05 Phosphorus: 1.38E-06 Phosphate: 3.95E-07	
GH – Hydro (Stoessel et al., 2012)	Ammonia: 9.44E-05 Nitrogen Oxides: 2.67E-05 Dinitrogen monoxide: 2.67E-05	Nitrate: 5.5E-05 Phosphorus: 1.38E-06 Phosphate: 3.95E-07	
VF – Aqua (Cohen et al., 2018)	Sulfur dioxide: 1.16E-02		
GH – Aqua (Cohen et al, 2018)	Sulfur dioxide: 1.16E-02		
Conventional (Stoessel et al., 2012)	Ammonia: 2.23E-04 Nitrogen Oxides: 6.32E-05 Dinitrogen monoxide: 6.32E-05	Nitrate: 1.3E-03 Phosphorus: 1.78E-06 Phosphate: 5.08E-07	

LIFE CYCLE INVENTORY | PACKAGING

Packaging was calculated to weigh 0.07123 kg and modeled as PET, granulate (Brenmar) to reflect a clear, plastic clamshell container. This packaging estimate was kept consistent across all growing systems.

36 Mahe, G. (2012). *Clarksville's Overlook Farm: Now Farm-Raising Tilapia.* St. Louis Magazine. Retrieved from https://www.stlmag.com/dining/Clarksvilles-Overlook-Farm-Now-Farm-Raising-Tilapia/.
37 Hindelang, M., Gheewala, S. H., Mungkung, R., & Bonnet, S. (2014). *Environmental Sustainability Assessment of a Media Based Aquaponics System in Thailand.* J. Sustain. Energy Environ., 5, 109-116.
38 Cohen, A., Malone, S., Morris, Z., Weissburg, M., & Bras, B. (2018). *Combined Fish and Lettuce Cultivation: An Aquaponics Life Cycle Assessment.* Procedia CIRP, 69, 551-556.
39 Benke, K & Tomkins, B. (2017). *Future Food-Production Systems: Vertical Farming and Controlled Environment Agriculture.* Sustainability: Science, Practice and Policy. 13:1, 13-26, DOI: 10.080/15487733.2017.1394054.

TRANSPORTATION | DISTRIBUTION CALCULATIONS-CONVENTIONAL

To calculate transportation impacts for the conventional agriculture LCA, we assumed that lettuce production would occur in Monterey County, California. We chose this region because California is the leading producer of lettuce in the U.S., and Monterey County produces 57% of California's lettuce production.[40] We assumed that the mode of transportation is by commercial truck, as a 2010 study shows that almost 100% of lettuce produced in California was transported to St. Louis by truck.[41] The route with the fewest miles driving from Monterey California to St. Louis, Missouri is 2,014 miles (Google Maps, 2019A). An estimated 20% of U.S. long-haul trucks are empty on their return trip.[42] We assumed that 20% of the time, the delivery trucks would return to California empty, and therefore increased the distance to 2,417 miles (2,014 miles + (2,014*0.2 return trip miles), or 3,889 kilometers. We did not count return trips that were used to carry goods from St. Louis to California.

TRANSPORTATION | DISTRIBUTION CALCULATIONS-CEA SYSTEM

We assumed that the soilless agriculture systems would take place within St. Louis, and that transportation would be for one ton of produce per trip in a short (less than 50 feet) refrigerated van hauling one ton of which typically makes short haul (<500 mile) trips.[43] We assumed that the soilless farm and all grocery stores would be within St. Louis, which is 21 miles long by ground transportation.[44] We chose 21 miles as the round-trip delivery distance with the assumption that the delivery van's average trip would be half the length of the city, and that the van would return empty to the farm.

40 Geisseler, D. & Horwath, W. (2016). *Lettuce Production in California.* Assessment of Plant Fertility and Fertilizer Requirements for Agricultural Crops in California. University of California, Davis. Retrieved from https://apps1.cdfa.ca.gov/FertilizerResearch/docs/Lettuce_Production_CA.pdf.

41 Paggi, M.; Noel., J., Yamazaki, F.; Hurley, S. & McCullough, M. (2012). *An Analysis of California Agricultural Transportation Origins, Destinations, Modal Competition and Industry Perspectives Selected Fresh Fruits and Vegetables*. Final Report: Grant 12-25-G-0083.Retrieved from http://www.fresnostate.edu/jcast/ifa/documents/1An%20Analysis%20of%20California%20Agricultural%20Transportation.pdf

42 Maynus, L. & Sheckler, R. (2009). *Empty Backhaul: An Opportunity to Avoid Fuel Expended on the Road.* Study Report 200911109. Prepared for the New York State Energy Research and Development Authority and the New York State Department of Transportation. Retrieved from https://www.dot.ny.gov/divisions/engineering/technical-services/trans-r-and-d-repository/C-0831%20Empty%20Backhaul%20Final%20Report.pdf.

43 National Highway Traffic Safety Administration (2015). *Phase 2 Fuel Efficiency Standards for Medium and Heavy-Duty Engines and Vehicles.* Retrieved from https://www.nhtsa.gov/sites/nhtsa.dot.gov/files/phase-2-hd-fuel-efficiency-ghg-final-ria.pdf.

44 Google Maps (2019B). City of St. Louis. Retrieved from https://www.google.com/maps/place/St.+Louis,+MO/@38.6530169,90.3835474,11z/data=!3m1!4b1!4m5!3m4!1s0x87d8b4a-9faed8ef9:0xbe39eaca22bbe05b!8m2!3d38.6270025!4d-90.1994042.

RESULTS

Using a single-score comparison with six grouped themes of impact areas to compare the five agricultural systems, our results show that conventionally grown lettuce produced in California and transported to St. Louis has the overall lowest environmental impacts [FIGURE 9]. After conventional lettuce, greenhouse hydroponic lettuce grown in St. Louis and distributed locally has the next lowest amount of environmental impacts. There were three main impact areas that WWF identified as important in the beginning of the study: contribution to climate change, land-use, and water use. In these three categories, conventional agriculture has the lowest impacts associated with climate change [FIGURE 10], primarily because of its lower electricity footprint and cleaner mix of electricity. However, greenhouse hydroponic agriculture received the lowest scores for land use [FIGURE 11] and water use [FIGURE 12] with vertical hydroponics in second, and then conventional agriculture.

FIGURE 9 COMPARATIVE IMPACT ASSESSMENT OF 18 IMPACT AREAS GROUPED INTO SIX THEMES

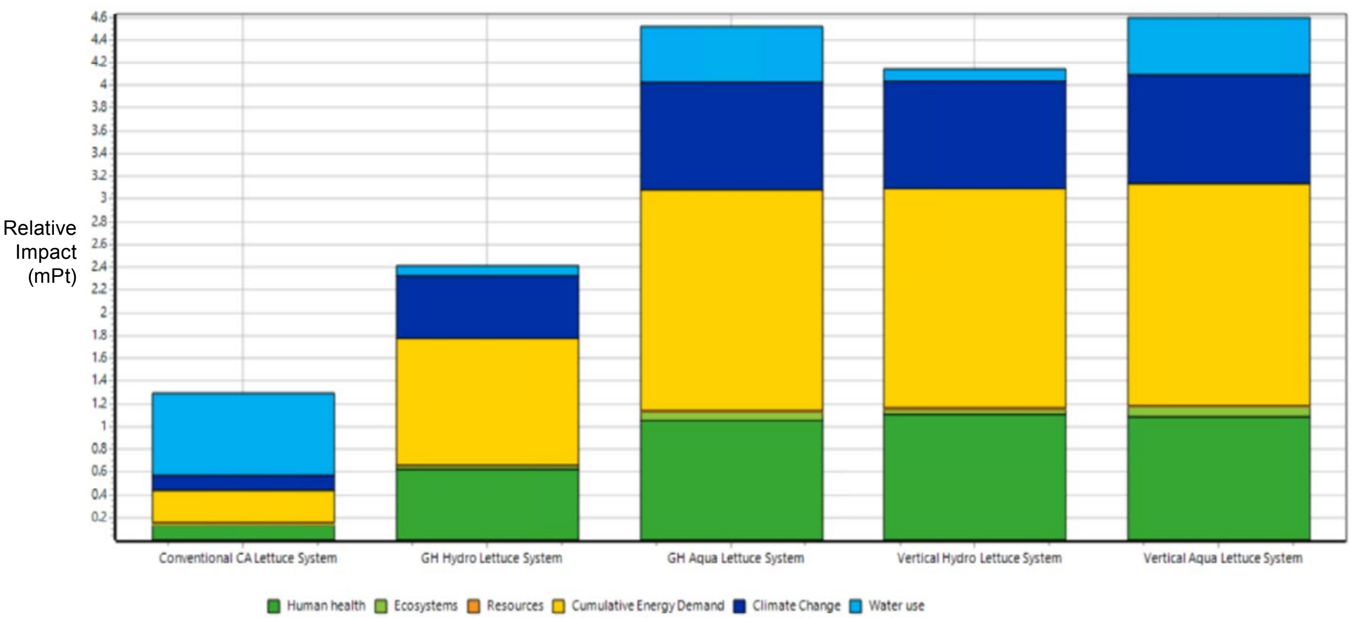


FIGURE 10 COMPARATIVE IMPACT ASSESSMENT: GREENHOUSE GAS EMISSIONS (IN KG CO2-EQ)

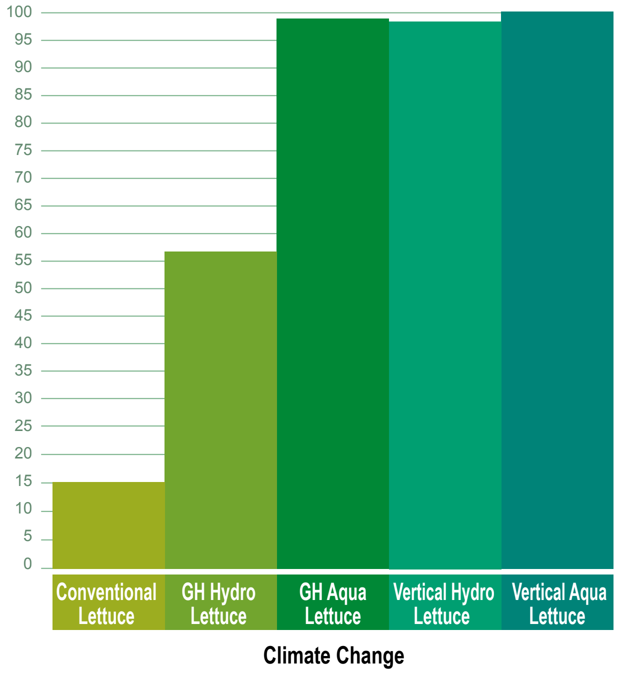


FIGURE 11 COMPARATIVE IMPACT ASSESSMENT: COMBINED DIRECT AND INDIRECT LAND-USE IN M2A (SQUARE METERS OCCUPIED FOR 1 YEAR)

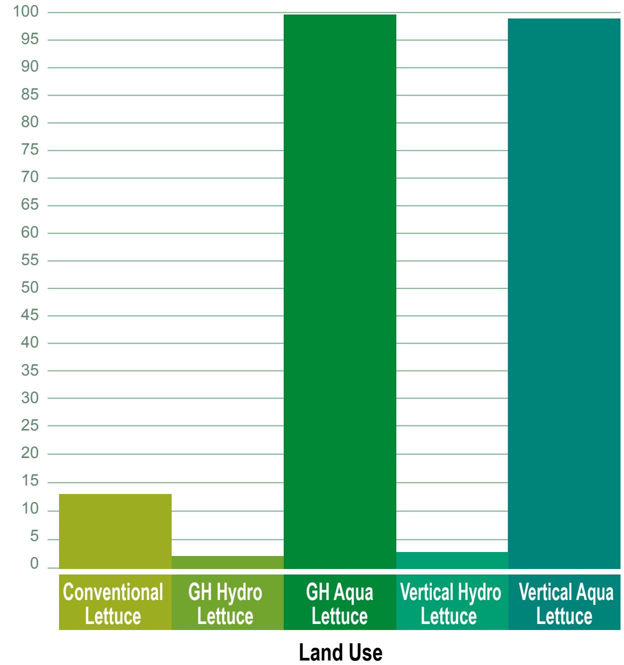


FIGURE 12 COMPARATIVE IMPACT ASSESSMENT: WATER CONSUMPTION IN M3

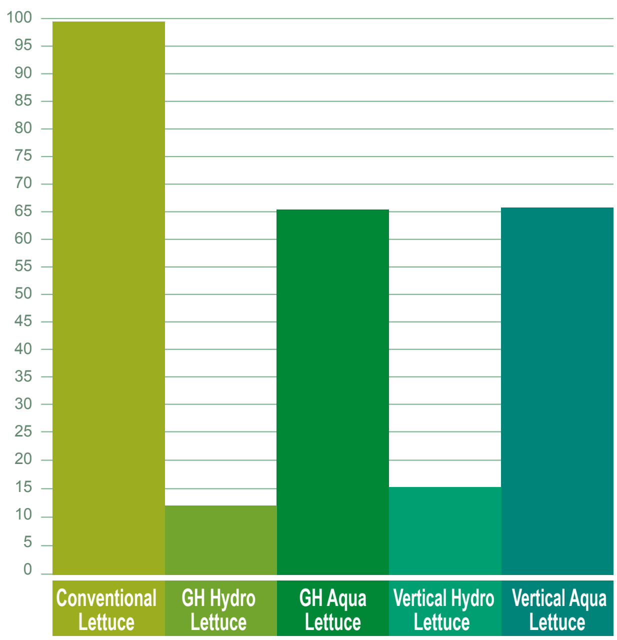
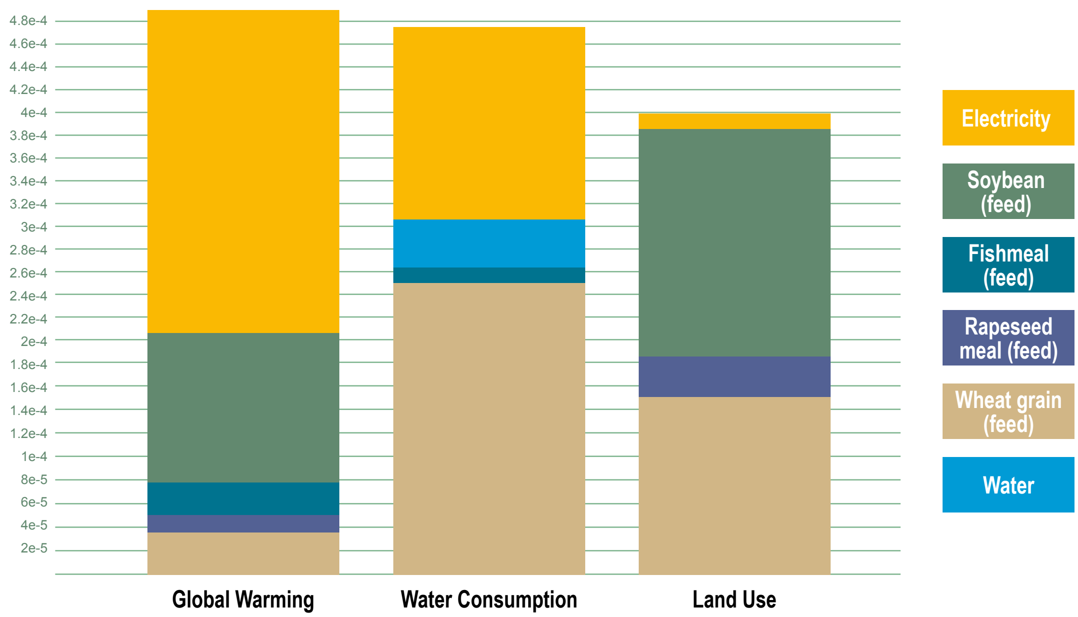


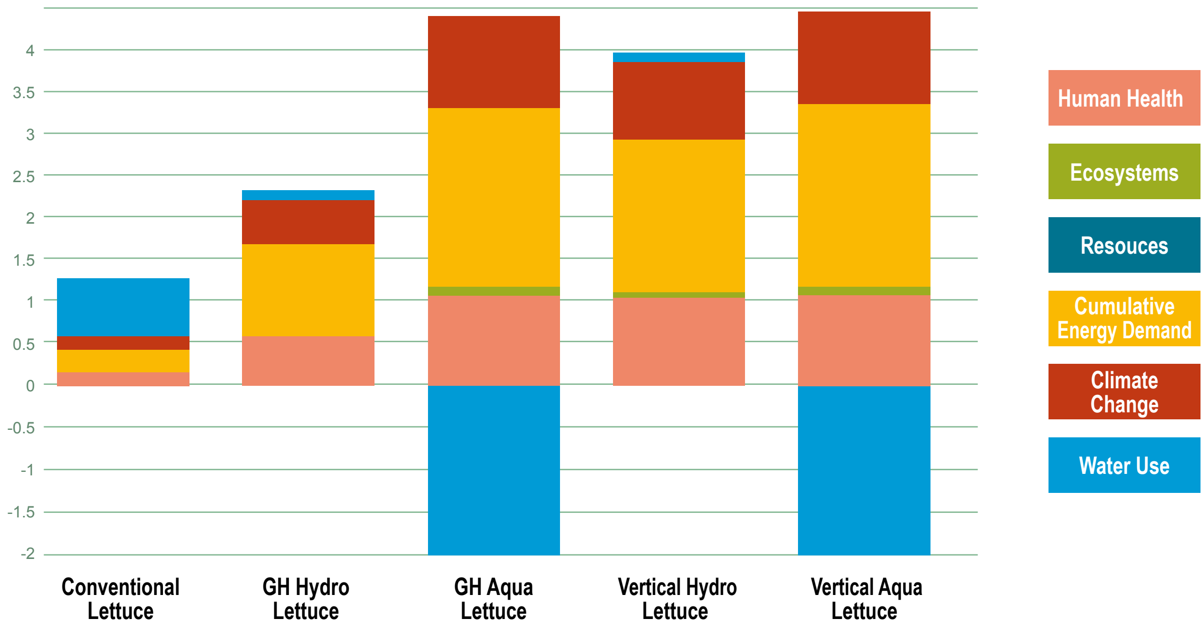
FIGURE 13 A PRODUCTION-STAGE IMPACT ASSESSMENT OF GREENHOUSE AQUAPONIC LETTUCE



Of the other impact areas, the four controlled environment agriculture systems all had higher impacts on human health and ecosystems relative to conventional agriculture [FIGURE 9]. The primary driver of the impacts to these two categories stem from the systems' different electricity usage and grid mixes. In addition to higher GHG emissions per kwh, the St. Louis electricity grid has higher ecosystem and human toxicity level impacts than California electricity.[45]

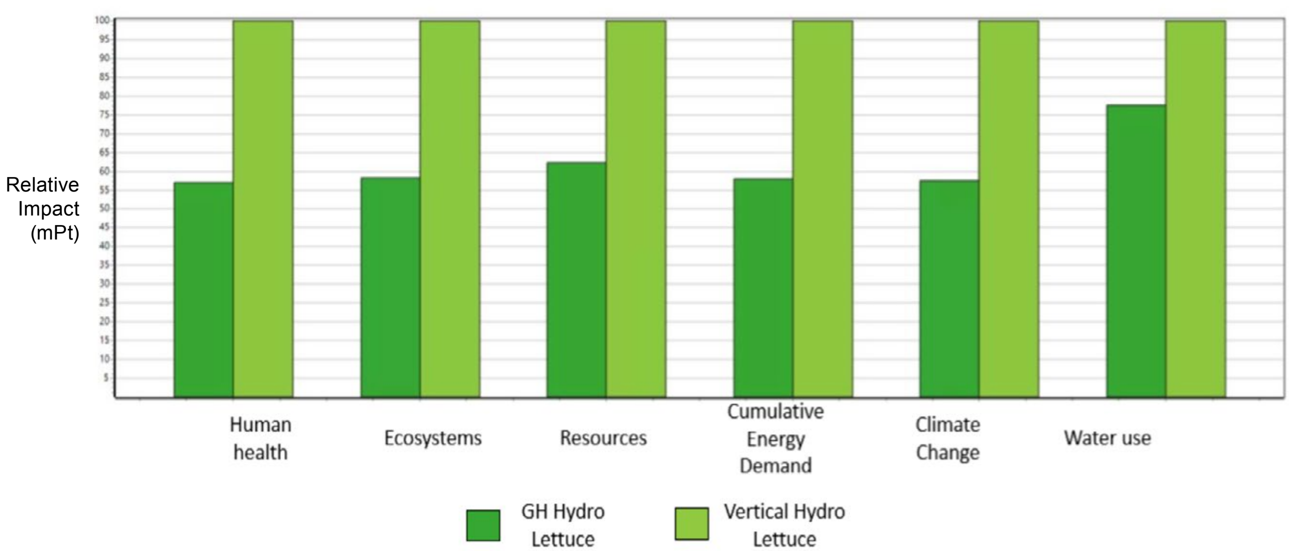
The two aquaponics systems show much higher environmental impacts than the other three systems [FIGURE 9]. This is because the two aquaponic systems include the cumulative environmental impacts for both the lettuce and tilapia; because this is one system which produced two products, the environmental impacts of the two commodities could not be separated. We allocated the environmental impacts based on the relative economic value of production and calculated an allocation of 75% of impacts going to lettuce and 25% of impacts going to tilapia. The main drivers for the environmental impacts in aquaponics, apart from electricity, come from tilapia feed, which particularly contributes to land and water use [FIGURE 13]. If St. Louis tilapia demand were fixed and this tilapia would replace tilapia that would otherwise be grown elsewhere, that would significantly reduce the environmental impacts of the two aquaponics systems relative to the other three. This LCA models this scenario as an avoided product credit in [FIGURE 14]. However, most markets do not have perfectly fixed demand, and adding one aquaponics farm to St. Louis would be more likely to increase the total amount of tilapia supply than to reduce tilapia grown elsewhere.

FIGURE 14 A COMPARISON OF THE SYSTEMS USING AN AVOIDED PRODUCT CREDIT FOR 0.2 KG OF TILAPIA INSTEAD OF ALLOCATION FOR THE TWO AQUAPONIC SYSTEMS



Of the two hydroponics systems, greenhouse hydroponic lettuce has a significantly lower footprint than vertical hydroponic lettuce across all six thematic groups [FIGURE 15]. The main driver of this difference is vertical agriculture's higher electricity use due to using LED lights as its primary source of plant light. Although vertical hydroponics has a smaller direct land-use footprint, it has a higher overall land-use footprint due to indirect land-use associated with its higher electricity use.[46]

FIGURE 15 COMPARISON OF GREENHOUSE AND VERTICAL HYDROPONICS AS A RATIO OF IMPACT



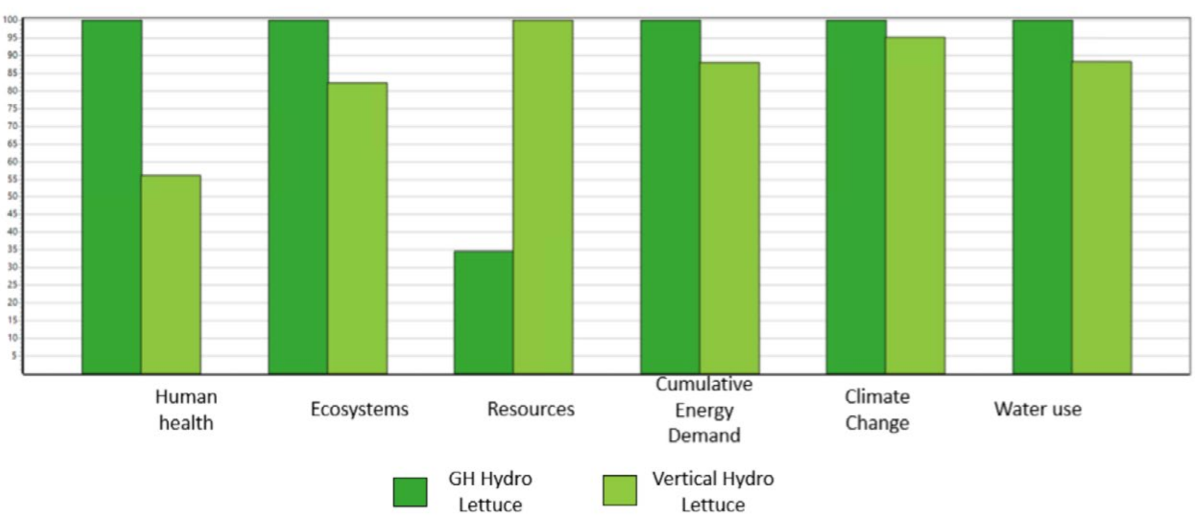
46 EcoInvent (2018). *The Ecoinvent Database Version 3*. The International Journal of Life Cycle Assessment 1(9). Accessed via SimaPro.

ANALYSIS AND DISCUSSION

Conventional agriculture currently has the lowest overall environmental impacts, but this may change in the near future as CEA technology improves and climate change makes conventional agriculture more challenging. The results section shows that, of the four controlled environment agriculture systems, greenhouse and vertical hydroponics have lower relative impacts than the two aquaponics systems. Of the two hydroponics systems, greenhouse hydroponics has lower environmental impacts than vertical hydroponics in the six grouped themes of impacts [FIGURE 15]. The primary driver for this disparity is that vertical agriculture uses more electricity than greenhouse agriculture. However, vertical agriculture uses more electricity primarily because of its need for LED lighting, which is a young technology that is developing rapidly.[47] Greenhouse agriculture's electricity use is driven primarily by temperature control, which is an established technology making smaller efficiency gains per year. To look at potential future environmental impacts, we modeled a hypothetical scenario where vertical hydroponic farming can reduce its electricity footprint by 20%, while greenhouse hydroponic farming keeps the same electricity footprint [FIGURE 16]. This graph compares the two systems within each category but is not normalized to compare the impacts across categories. In this scenario, the vertical hydroponic system still has higher environmental impacts across all 18 impact areas relative to greenhouse farming. This suggests that a greenhouse hydroponic system would be the better environmental choice in St. Louis, even if LED lighting becomes substantially more efficient in the near future.

FIGURE 16 COMPARISON OF GREENHOUSE AND VERTICAL HYDROPONICS AS A RATIO OF IMPACTS IN A HYPOTHETICAL FUTURE SCENARIO WHERE VERTICAL HYDROPONICS USES 20% LESS ELECTRICITY THAN PRESENT

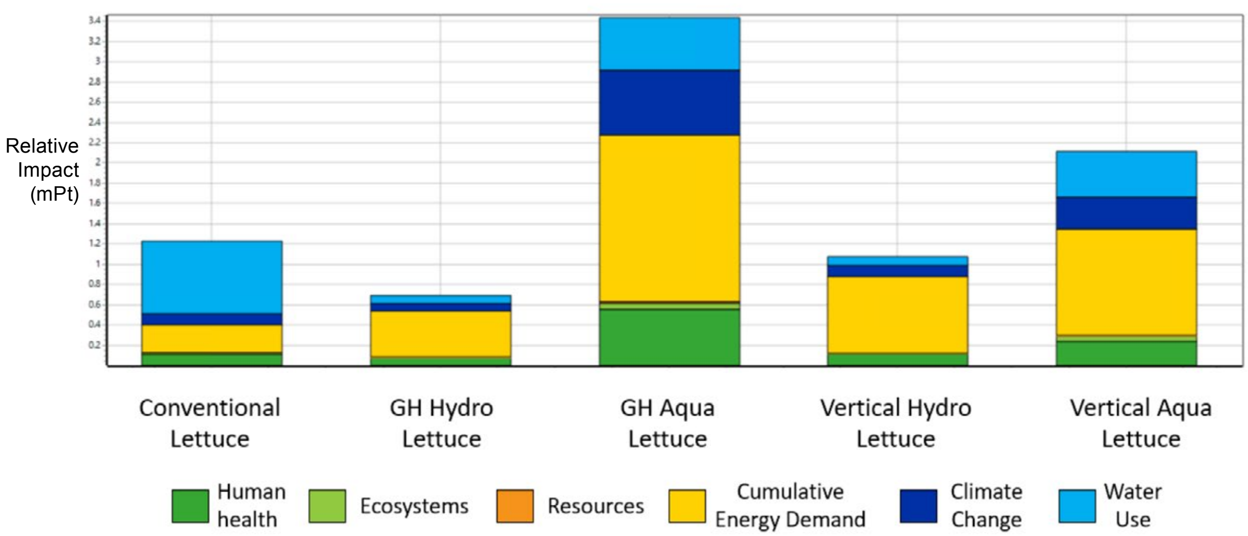
Relative Impact (mPt)



47 Bergesen, J. D., Tähkämö, L., Gibon, T., & Suh, S. (2016). *Potential long-term global environmental implications of efficient light-source technologies.* Journal of Industrial Ecology, 20(2), 263-275 Retrieved from https://onlinelibrary.wiley.com/doi/pdf/10.1111/jiec.12342.

One reason that the four CEA systems had higher environmental impacts than conventional agriculture in 13 out of 18 impact areas [FIGURE 9] is because of CEA agriculture's higher electricity use in the context of a typical St. Louis mix of electricity including fossil fuels, nuclear, and renewable energy.[48] We modeled a hypothetical scenario where the electricity use for all five systems is sourced from U.S. photovoltaic solar power instead of the standard regionally specific mixes [FIGURE 17] – this model uses region-specific solar power levels to capture the variations in photovoltaic conversion due to climate. In this model, greenhouse and vertical hydroponic systems have overall lower environmental impacts than conventional agriculture, with drastically lower level impacts on human and ecosystem health. Modeling with other sources of renewable energy like wind power show similar results. This suggests that either hydroponics systems would be a more environmentally sustainable choice than conventionally grown lettuce if the farm is able to directly source solar electricity, or else pay to receive solar credits.

FIGURE 17 COMPARISON OF ALL FIVE SYSTEMS AS A RATIO OF IMPACTS ASSUMING ALL ELECTRICITY IS SOLAR-GENERATED



48 EcoInvent (2018). *The Ecoinvent Database Version 3*. The International Journal of Life Cycle Assessment 1(9). Accessed via SimaPro.

RECOMMENDATIONS AND CONCLUSIONS

With current technology efficiency, electricity sources, and natural resource availability, conventional agriculture has the lowest total environmental impacts of the five agricultural systems that we modeled. However, California's climate is changing, and production of water-hungry specialty crops like lettuce may become less viable in the next few decades. Concurrently, technology for controlled environment agriculture is becoming more efficient each year, which will reduce its overall environmental impacts over time. Further, if hydroponics farms source their electricity from renewable energy like solar instead of the standard regional mix used by St. Louis, then both greenhouse and vertical hydroponics farms would have lower environmental impacts than conventional agriculture. Another possible option is to make use of St. Louis' stranded assets by partnering with electricity plants to use surplus energy during certain times of day.

Out of the indoor, soilless farming options, a greenhouse hydroponics farm would be the most environmentally sustainable choice for the St. Louis region for the foreseeable future, until LED technology can make significant enough efficiency gains to reduce the energy footprint of vertical agriculture. Situating the greenhouse on otherwise unused space like a building roof could further reduce the environmental impacts of greenhouse hydroponic agriculture by reducing its land-use footprint.

THE MARKETS INSTITUTE AT WWF | INNOVATION ANALYSIS

APPENDIX II

Optimal Conditions for Controlled Environment Agriculture: A Summary

Caroline Schulte and Jessica Hauda

WWF

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CONTENTS

Indoor, soilless farming encompasses a variety of growing techniques and tools. There are few best practices, many considerations, and the technology is rapidly evolving. Choices around technology, systems, and crops also affect where a farm should be located and what opportunities and hurdles will be most important. Below, we have included an in-depth explanation and analysis of each type of system, the various technologies that are required or suggested with pros and cons, and the ideal growth conditions for several popular crops. This report is meant to serve as a resource as decisions are made about where to situate a farm, what system and technology to use, and what to grow.

TECHNOLOGY

GREENHOUSE TECHNOLOGY

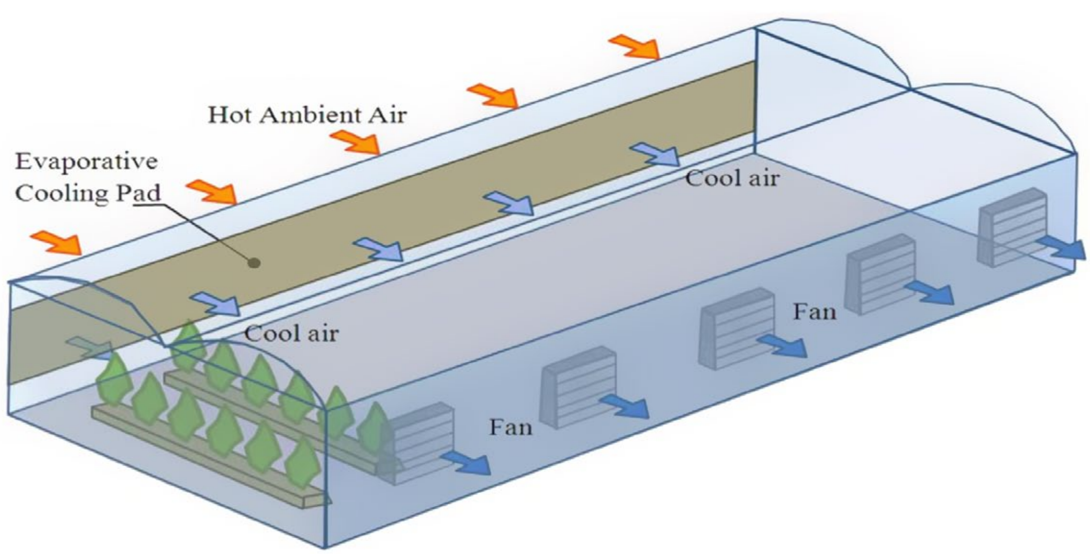
Greenhouses are framed structures aligned by transparent material used for the cultivation of plants.[1] The level of control varies from basic shelters to fully computerized enclosures.[2] Greenhouse technology can include control of cooling, heating, ventilation, humidity, carbon dioxide, and fertigation. Required technology includes energy sources, covering or glazing materials, structural components, a plant culture system, and lighting.

Cooling can be accomplished in a variety of ways. Evaporative cooling is based on the conversion of sensible heat into latent heat. While it is the cheapest option, it demands high quality water and can decrease plant transpiration. An alternative to evaporative cooling is mechanical refrigeration, yet this method is extremely expensive and energy inefficient for greenhouses. Thus, evaporative cooling is the most common technique primarily incorporated using fan and pad or, to a lesser extent, by fog cooling.

High pressure fog cooling is when small drops of water are supplied for effective evaporation. This requires high pressure nozzles delivering small drops of water. While it is low in cost and has a high cooling effect, it requires forced ventilation, is difficult to control the water, and the miniscule nozzles tend to get clogged. On the other hand, fan and pad cooling entails placing fans on one side of the enclosure and wet pads on the opposite side. Outside air is sucked into the greenhouse by ventilation fans through the wet pads, allowing it to be humidified and cooled. Air is then removed by the fans at the opposite ends. It has an 80-90% efficiency with simple control and ease of operation. Some downsides include that it can be high in cost, lacks uniformity of climate conditions, electric power failures turn the system into a heat trap, and it can overuse water.

FIGURE 1 FAN AND PAD COOLING FOR GREENHOUSES

Franco-Salas, Antonio & Valera, Diego & Peña, Araceli. 2015. *Energy Efficiency in greenhouse evaporative cooling techniques: cooling boxes versus Cellulose Pads.* 10.13140/RG.2.1.4375.2808. https://www.researchgate.net/figure/Evaporative-cooling-boxes-in-greenhouse_fig2_280232538



1 Rorabaugh, Patricia A. *Introduction to Hydroponics and Controlled Environment Agriculture.* Revised July 2015.

2 Vox, Giuliano & Teitel, M. & Pardossi, Alberto & Minuto, Andrea & Tinivella, Federico & Schettini, Evelia. (2010). *Chapter 1: Sustainable Greenhouse Systems. Sustainable Agriculture: Technology, Planning and Management*, Augusto Salazar e Ismael Rios Editors, Nova Science Publishers, Inc. NY USA.

FIGURE 2 FOGGING TECHNIQUE FOR COOLING OF GREENHOUSES

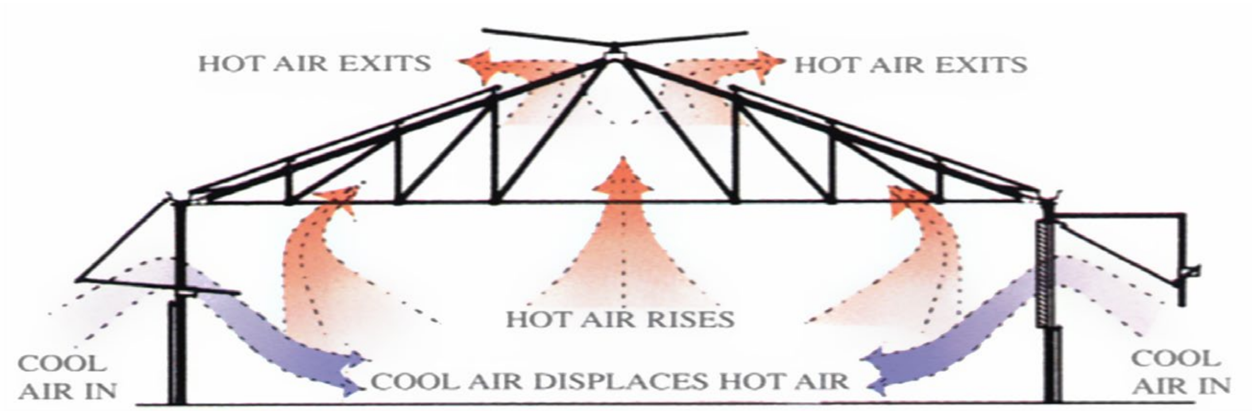
Heating systems are made up of a fuel supply, fuel burner, heat exchanger, heat distribution system, and a control unit. Heating systems can be central or local. Central means the boilers are located in separate houses outside of the main controlled environment. Consequently, a distribution system connecting the two houses is required. Local systems release heat directly into the greenhouse as the furnace is within the greenhouse space. Heating can be accomplished using steam, hot water, hot air, or infrared. There are also solar thermal systems that are more sustainable.[3]

Ventilation prevents excessive rises in temperature and humidity. This can be done naturally or using forced ventilation. Natural ventilation is driven by a pressure field induced by wind around the controlled environment and buoyancy induced by the warmer and more humid air. This uses less energy and is achieved by opening windows at the top of the greenhouse or in the sidewalls. Forced ventilation is accomplished through fans moving large quantities of air. Most commonly, axial fans are used and mounted on sidewalls to minimize shading.[4] For example, fan and pad cooling is a form of forced ventilation.

3,4 Vox, Giuliano & Teitel, M. & Pardossi, Alberto & Minuto, Andrea & Tinivella, Federico & Schettini, Evelia. (2010). *Chapter 1: Sustainable Greenhouse Systems. Sustainable Agriculture: Technology, Planning and Management,* Augusto Salazar e Ismael Rios Editors, Nova Science Publishers, Inc. NY USA.

FIGURE 3 NATURAL VENTILATION OF GREENHOUSES

Monk, Daniel. *Natural Ventilation.* The Grower's Guide to ROI |Commercial Greenhouse Tips. https://danieljmonk.com/



With regards to humidity, step cooling with fans can be used to decrease temperatures.[5] Ridge vents or side vents for ventilation can be used to let out humidity as well. Fogger systems can be used to increase humidity, whereas heaters can be used to decrease humidity. In general, highly humid regions should not use evaporative cooling techniques.[6] High humidity should be avoided as it generates fungal infections.[7]

In addition, carbon dioxide levels should be kept below 5000 ppm. Growers need to decide if CO2 enrichment is worth it because it comes at a high cost. CO2 tanks, injector systems, and CO2 monitors must be used. Having CO2 of at least 400 - 450 ppm is necessary to maintain ambient levels. Most growers supplement CO2 to 800 - 1500ppm.

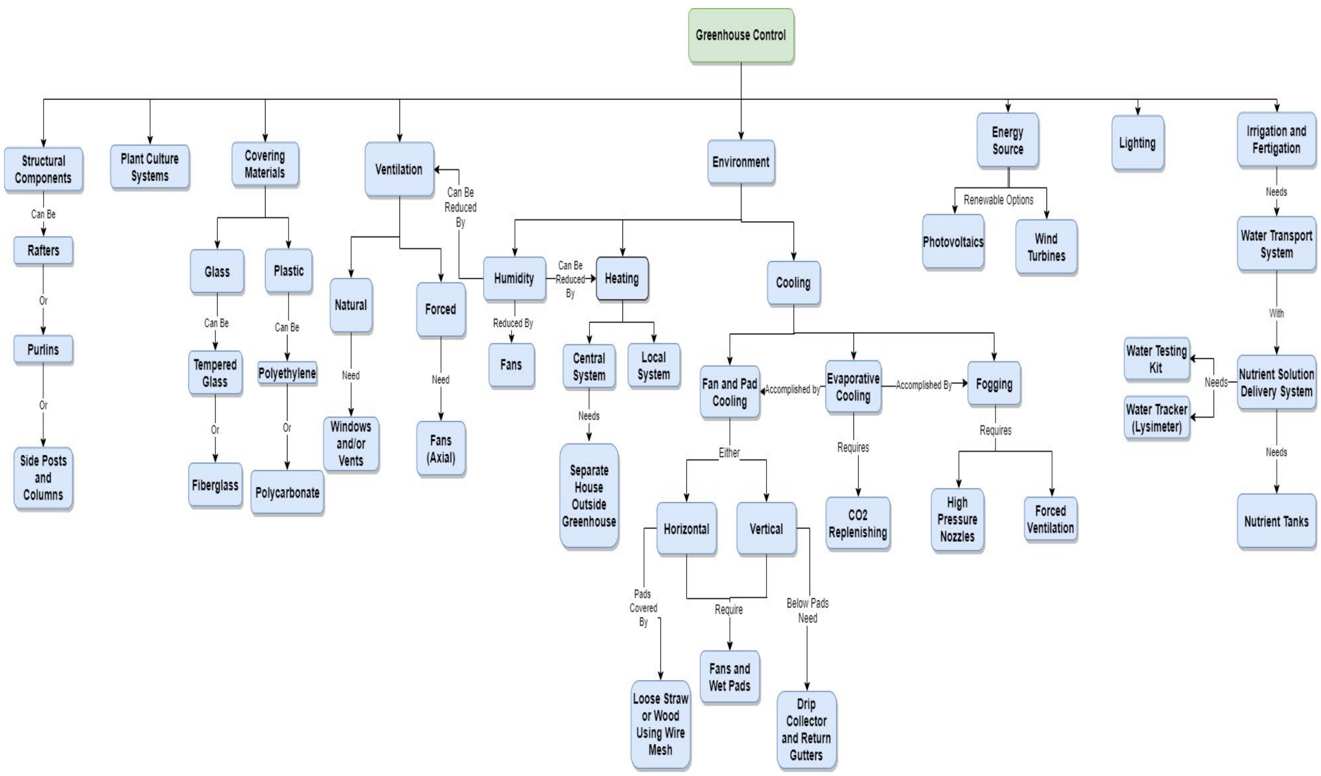
Fertigation is the injection of fertilizer and water. A system - such as lysimeters - is required to monitor the water usage of the plants.[8] The solution flowing through the system also needs to be checked for pH and EC content to determine if any substance is scarce (fertilizer, acid, water, nutrients, etc.). Irrigation technology is used to accomplish this; irrigation technology is dependent on the type of plant culture system being integrated within the greenhouse[9] [see HYDROPONIC TECHNOLOGY section for more details]. Additionally, there must be a fertigation head unit.

There are abundant energy sources that can be used to run greenhouses. Some sustainable options are photovoltaics or wind turbines. Similarly, there are many options for covering or glazing materials. Glass is a very common option. It provides good crop protection under weather conditions, has the best light transmission, and is clear. Unfortunately, it is extremely heavy (requiring an excess of support members), has high heat loss and high initial investment, and requires an abundance of maintenance.[10] Polyethylene is also commonly used to cover large greenhouses because it's inexpensive and easily maintained. In addition, it is translucent which provides semi-diffused light and retains heat well. However, it does only last 3-5 years and is subject to stretching and sagging in windy or snowy locations. Finally, polycarbonate - another covering option - is durable, lightweight, high quality, and clear. Yet, it lacks heat retention.[11]

5, 9 Pickens, Jeremy M, et al. *Greenhouse Crops and Cropping Systems for Commercial Aquaponics.* Southern Regional Aquaculture Center, United Stated Department of Agriculture, Aug. 2016.
6 Schulte, Caroline, and Stacy Tollefson. *Optimal Conditions of Crops Overview.* 26 Aug. 2019.
7 Vox, Chapter 1: *Sustainable Greenhouse Systems.*
8 Schulte, *Optimal Conditions of Crops Overview.*
10 Stevens, Alan. *Starting a Greenhouse Business: A Commercial Growers Guide.* Kansas State University, 1994.
11 Cowan, Shannon. *Greenhouses: How to Choose and Where to Buy*. Eartheasy Guides & Articles, learn.eartheasy.com/guides/greenhouses-how-to-choose-and-where-to-buy/.

Structural components include rafters for primary vertical support, perlins which are horizontal supports that run from rafter to rafter, and side posts and columns.[12] With regards to a plant culture system, refer to the hydroponics section. Finally, lighting can be artificial or natural. Artificial light can be from LEDs (light emitting diodes) or HPS (high pressure sodium). LEDs add less heat but are more expensive.[13] Knowing that there is high cloud coverage from about November to May in St. Louis, artificial light might be necessary. In general, shade over a greenhouse should only be used to keep the temperature in check.[14] Otherwise, natural sunlight should be utilized in the greenhouse.

FLOW CHART 1 GREENHOUSE TECHNOLOGY REQUIREMENTS



12 *Greenhouse Structures: Ornamental Production.* Aggie Horticulture®, Texas A&M.
13 Pickens, Greenhouse Crops and Cropping Systems for Commercial Aquaponics.
14 Schulte, Caroline, and Stacy Tollefson. *Optimal Conditions of Crops Overview.* 26 Aug. 2019.

HYDROPONICS TECHNOLOGY

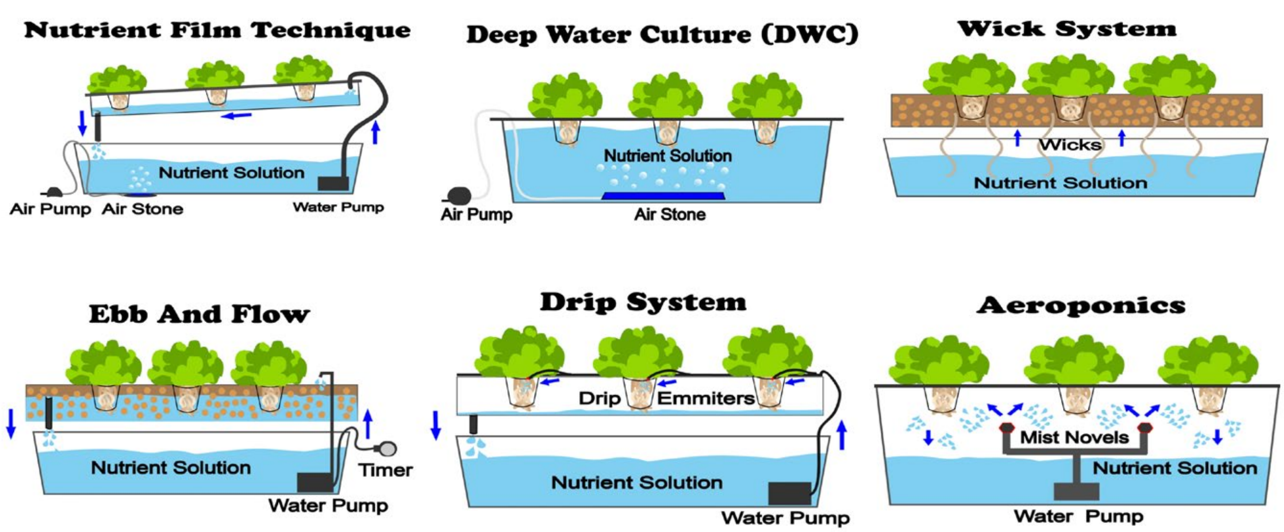
Hydroponics is an application of soilless farming.[15] Root zone environments are controlled in hydroponics and a nutrient solution is used with every watering.[16] A hydroponic system must include the plant culture system, water equipment, fertigation units, and nutrients. When it comes to control of the environment, this depends on the amount of control desired [see GREENHOUSE TECHNOLOGY section for control options].

The plant culture system can be either opened or closed. Most commonly, open systems are adapted. However, with environmental concerns, closed systems should be utilized more often.[17] Closed loop systems recycle water while open cycle systems drain the nutrient solutions after one application.[18] Additionally, the system can either be a liquid culture or aggregate culture. Liquid culture systems have roots hanging in a nutrient solution (being a mist or liquid). Aggregate culture systems have the roots growing in an inert media which is irrigated with the nutrient solution. The main hydroponic systems are aeroponics (liquid and closed or open), aquaponics (liquid and closed or open), drip system (aggregate and closed or open), deep water culture (DWC) (liquid and closed), ebb and flow (aggregate and closed), nutrient film technique (NFT) (liquid or aggregate and closed), and wick (aggregate and closed).

Aeroponics is the application of nutrient solutions via ambient air; essentially, roots are suspended within the air and then sprayed with nutrient solution.[19] Aquaponics is the combination of aquaculture - the farming of aquatic species - with hydroponics - soilless crop production [see AEROPONIC TECHNOLOGY section and Aquaponic Technology section for more details]. A drip system delivers nutrient solution to each plant through irrigation lines and emitters. DWC is the cultivation of crops in boards floating on top of nutrient solutions. Ebb and flow systems flood roots growing in an aggregate medium for a short period of time with nutrient solutions, then drain the water away. Ebb and flow systems are typically used for seedlings and nurseries. In NFT, roots are resting in inclined tubes or troughs which have nutrient solutions continually flowing through them. The wick system (rarely used at a commercial level) is when roots are grown down through an aggregate medium laced with a wick (absorbent material). The wick is suspended below the crop and submerged into the nutrient solution, allowing it to bring nutrients up into the medium.[20]

FIGURE 4 6 DIFFERENT TYPES OF HYDROPONIC SYSTEMS

NoSoilSolutions. https://www.nosoilsolutions.com/6-different-types-hydroponic-systems/



15 Koplow, Carol, and National Agricultural Library (U.S.). *Hydroponics.* Beltsville, Md.: National Agricultural Library, 1991.
16 Rorabaugh, Patricia A. *Introduction to Hydroponics and Controlled Environment Agriculture.* Revised July 2015.
17, 18, 19 Nicoletto, Carlo, et al. *Hydroponic Technologies.* Aquaponics Food Production Systems, by Carmelo Maucieri, Springer International Publishing, 2019, pp. 77–110.
20 Rorabaugh, Patricia A. Introduction to Hydroponics and Controlled Environment Agriculture. Revised July 2015

The most common approach to soilless culture in greenhouses currently is drip irrigation.[21] For a drip irrigation system, there must be pressurized irrigation lines, a pressure regulator with gauge monitors, a distribution pipeline, a header line, and tubing with emitters. The tubing is generally made of small diameter polyethylene with a drip line being approximately ¾ inch diameter polyethylene pipe, PVC, or vinyl lay flat hose. The plants are always placed in a substrate (either in channels, bags, or containers), and then the emitters are placed so that the roots of the crops receive water. A valve between the distribution pipeline and the header line is required to ensure that the irrigation can be turned on or off.

Nutrient film technique (NFT) requires roots of crops to lie on the bottom of a trough as the crops themselves are placed in equally spaced holes in the trough. The channel width and the water flow rates vary with relation to the crop type being grown. The length of the trough also varies from 1-20m depending on the size of the greenhouse. The trough material can be polyethylene liner, PVC, polypropylene, aluminum, or coated metal. The troughs need to be placed on a slope ranging from 1 -2% in incline; the nutrient solution enters from the upper end of the inclined area and drains out at the lower end. There must be a way to collect the drainage water and return it to the nutrient storage tank, as well as an irrigation system to supply nutrients to the troughs. The nutrient solution must be continually applied (or frequently cycled, i.e. 5 minutes on, 5 minutes off) to keep the roots wet, and only a thin layer of solution should be running through the troughs.[22]

Deep flow technique (DFT or DWC) keeps roots continually submersed in moving or stagnant nutrient solution. The depth of the tanks should be 15 - 30 cm, and the width should be around 100 - 240 cm. The plants are secured in holes on the floating polystyrene panels. This can be done by planting the seeds in a substrate polyurethane foam or rockwool cube that fits into the holes on the panels. The panels float on top of the water or they can rest on the trough sidewalls if there is an edge to support them. Dissolved oxygen content of the water is critical and can be maintained by flowing water or by introducing air through a manifold system or bubblers.

FIGURE 5 DRIP IRRIGATION SYSTEM IN GREENHOUSE

© Maxvis/Getting Images

FIGURE 6 NFT IN COMMERCIAL SETTING

How Hydroponics Can Boost Your Profit. Rimol Green House Systems. May 8, 2017, https://www.rimolgreenhouses.com/blog/how-hydroponics-can-boost-your-profits.

© Maxvis/Getting Images

FIGURE 7 DEEP FLOW TECHNIQUE

Espiritu, Kevin. *Deep Water Culture*. Epic Gardening. November 30, 2019, https://www.epicgardening.com/deep-water-culture-get-started/

© Maxvis/Getting Images

21, 22 13.2.2.3 Nutrient Film Technique. *Soilless Culture: Theory and Practice.* Michael Raviv et al., Academic Press, an Imprint of Elsevier, 2019, pp. 587–635.

With the plant culture systems, substrates are necessary for the plants as a substitute for soil. Substrates anchor plant roots, support plants, and provide water retention. There are organic substrates and inorganic substrates.[23] Organic substrates originate from plant residuals and are thus subjected to biological degradation.[24] These include coconut fiber, wood-based substrates (straw), and peat (a species of moss). Coconut fiber is ideal because it has a high pH, low environmental impact, high water retention, and air capacity capabilities. Wood substrates have good air content, but low water retention and poor aeration compared to coconut fiber. Rockwool is a very popular substrate in hydroponics due to its water retention and versatility, but it is not biodegradable. Inorganic substrates include rockwool, sand, perlite, and vermiculite *[see Nicoletto reference for more information and comparisons]*. Substrate containers are also necessary. These include channels, bags, or pots/trays (depending on the plant culture system being used).

Water equipment includes storage and supply units. Additionally, water disinfection units must be installed in closed hydroponic systems and irrigation systems. This is because in closed hydroponic systems, the water is being recycled; if there is any malnutrition or pesticide, it may spread without disinfection. Consequently, if there is a closed system, the solution drainage must go through the disinfection and nutrition monitoring and control unit before returning to the nutrient storage tank.[25] Drainage facilities used to capture the drainage solution are also important. These require piping and pumps.

The fertigation head unit supplies the crops with nutrients and water. This can be done using either nutrient tanks with pumps or injectors. Either system requires nutrients.[26] An acid tank is generally also necessary to lower pH.[27] With nutrient tanks, there are typically two tanks - tank A and tank B. Tank A has the nutrients calcium, nitrate, ammonium, and iron chelate. Tank B has the sulphates and phosphates. Monitoring systems are used to determine the EC (total amount of salts in the solution) and pH of the outgoing irrigation solution. Lab analyses are required to determine how many and which nutrients are being supplied in the nutrient solution being delivered to the crops. Another option is using an automatic injector that directly puts fertilizer into the irrigation pipe. It is important to note that in the case of aquaponics, the fertigation head unit is the fish tank or the sump tank [see **AQUAPONIC TECHNOLOGY** section for more information].

TABLE 1 GROWING MEDIA COMPARISONS

Somerville, Christopher. *Small Scale Aquaponic Food Production: Integrated Fish and Plant Farming.* Food and Agriculture Organization of The United Nations, 2015. http://www.fao.org/3/a-i4021e.pdf

Characteristics of different growing media

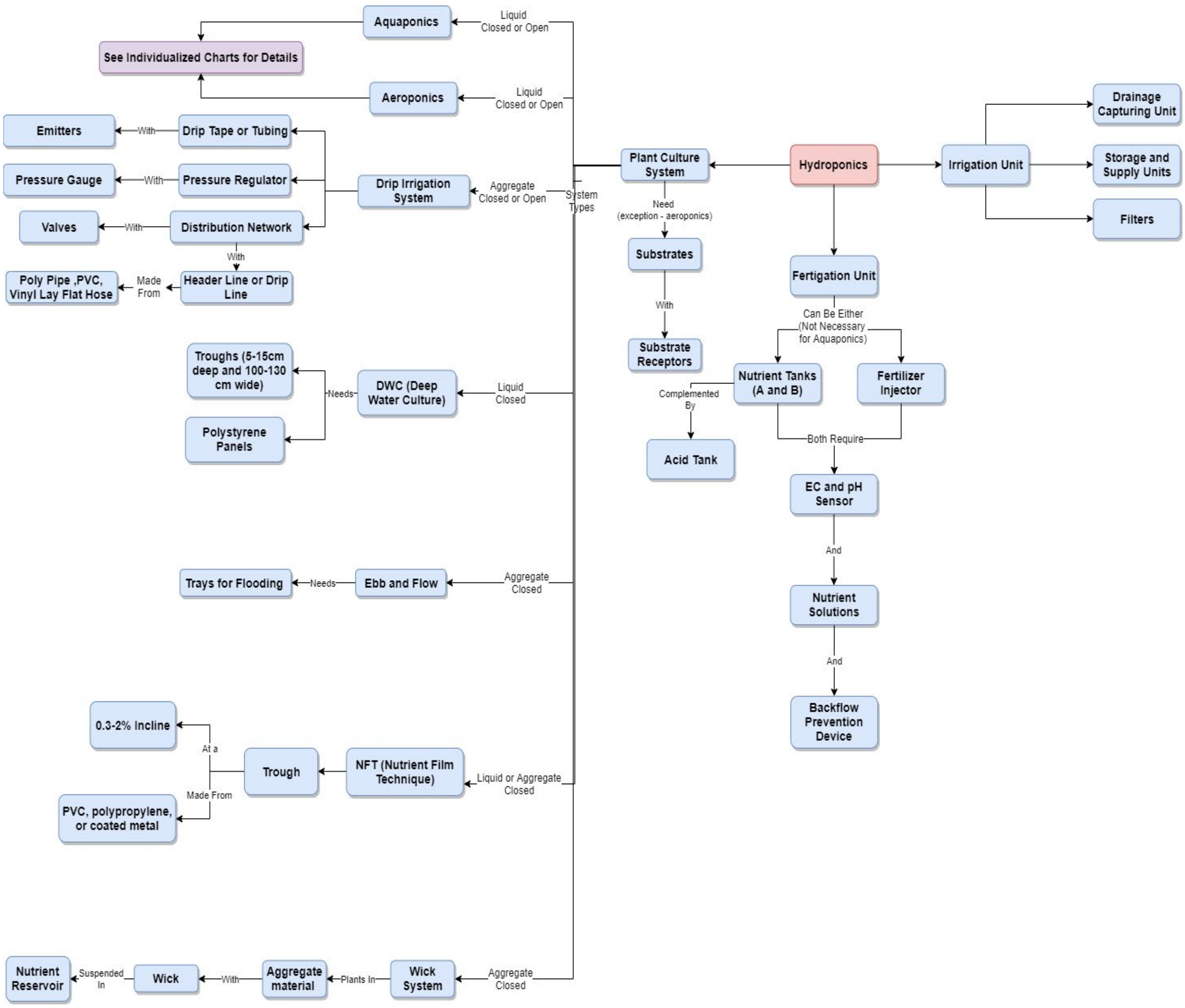
Media type	Surface area (m^2/m^3)	pH	Cost	Weight	Lifespan	Water retention	Plant support	Ease to work with
Volcanic gravel (tuff)	300–400	Neutral	Medium	Medium	Long	Medium–Poor	Excellent	Medium
Volcanic gravel (pumice)	200–300	Neutral	Medium–High	Light	Long	Medium	Medium–Poor	Easy
Limestone gravel	150–200	Basic	Low	Heavy	Long	Poor	Excellent	Difficult
Expanded clay (LECA)	250–300	Neutral	High	Light	Long	Medium–Poor	Medium	Easy
Plastic bottle caps	50–100	Inert	Low	Light	Long	Poor	Poor	Easy
Coconut fibre	200–400 (variable)	Neutral	Low–Medium	Light	Short	High	Medium	Easy

23 Nicoletto, Carlo, et al. *Hydroponic Technologies.* Aquaponics Food Production Systems, by Carmelo Maucieri, Springer International Publishing, 2019, pp. 77–110.

24, 25, 26 Savvas, Dimitrios. *Hydroponics: A Modern Technology Supporting the Application of Integrated Crop Management in Greenhouse.* Semantic Scholar, Department of Floriculture and Landscape Architecture, 4 Jan. 2003.

27 Schulte, Caroline, and Stacy Tollefson. *Optimal Conditions of Crops Overview.* 26 Aug. 2019.

FLOW CHART 2 HYDROPONIC TECHNOLOGY REQUIREMENTS



AEROPONIC TECHNOLOGY

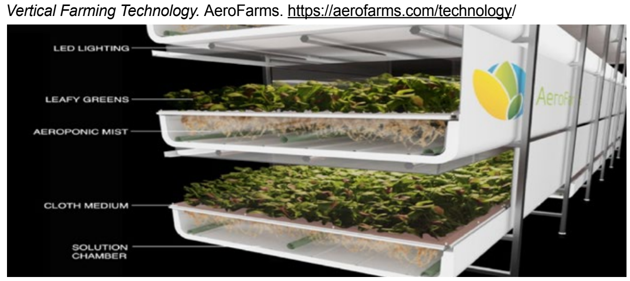
Aeroponics is known as the nourishment of plants using mist laced with nutrients.[28] To accomplish this, the plants need irrigation and fertigation units, along with growth chambers and a plant support system.

The irrigation and fertigation units require reservoirs for the nutrients and the water (either together or separate) as stated in the HYDROPONICS section. There must also be water and nutrient pumps that allow water to be transported from the reservoirs to the misting system. These pumps are connected to some form of piping, such as PVC. A repeat cycle timer is vital to control when water is dispersed into the system so misters can relay it to the plants. Finally, misting nozzles are required for the actual misting portion of the system. These should be between 5 and 50 microns.[29] The misting system can be low pressure or high pressure. High pressure is recommended for commercial systems and relies on pressurized water tanks capable of holding 60-90 psi with top quality misters. High pressure systems are more effective in their delivery of the solutions. Low pressure systems rely on fountain pumps to spray water through misters.[30]

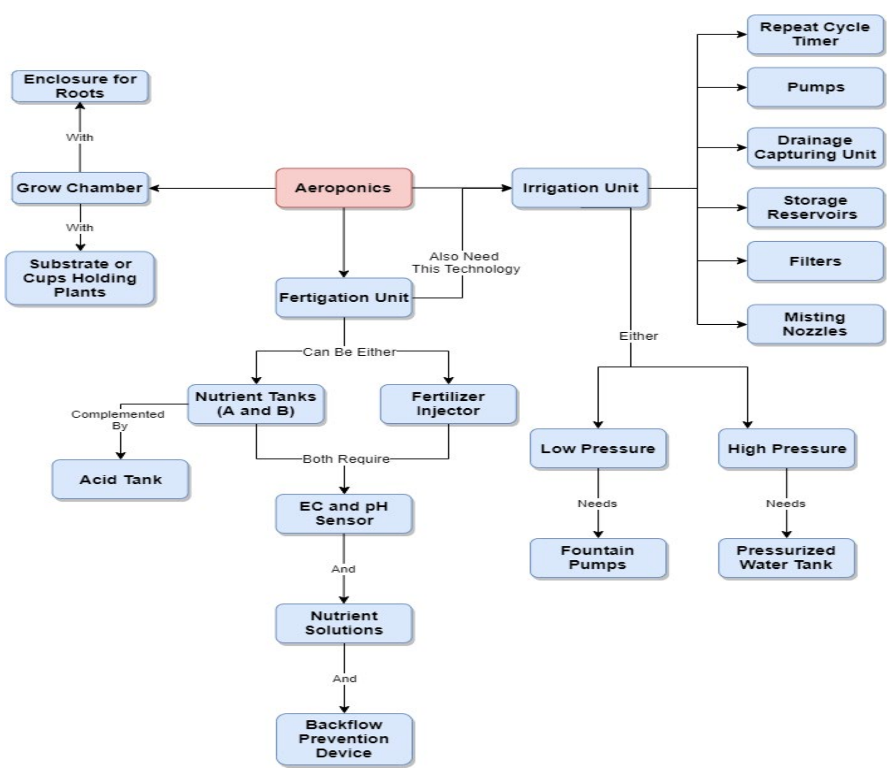
The grow chambers need to allow the roots of the plants to be enclosed. This is done in order to prevent light from reaching the roots and to hold in humidity. Typically, these enclosures are made from plastic bins.[31] To hold the plants, there are an abundance of options. One is that plants are inserted into Styrofoam boards with holes spread out evenly. Such boards are suspended on top of the grow chambers so the roots hang into the chambers while the boards shade the roots from above lighting. The plants are put in a medium or cup,[32] which cements the seeds into the boards. Aerofarms, a commercial food production company, has created their own reusable cloth that acts as a medium and a type of board for the plants.

FIGURE 8 NFT IN COMMERCIAL SETTING

Vertical Farming Technology. AeroFarms. https://aerofarms.com/technology/



FLOW CHART 3 AEROPONIC TECHNOLOGY REQUIREMENTS



28, 30, 31 Barth, Brian. *How Does Aeroponics Work?* Modern Farmer, 26 July 2018.
29, 32 Lisa. *Your Ultimate Guide to Aeroponics: Everything You Need to Know for Maximum Plant Yields.* The Practical Planter, 13 June 2019.

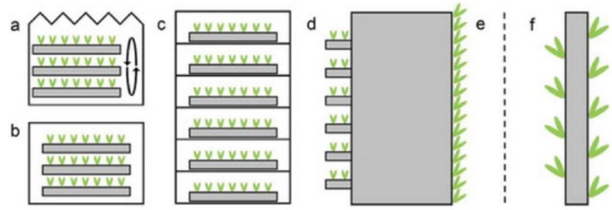
VERTICAL FARMING TECHNOLOGY

Vertical farming utilizes hydroponic systems to grow plants in a vertical fashion. Just like hydroponics and greenhouses, fertigation and irrigation units are necessary along with plant culture systems [see Hydroponic Technology for such components]. The environment can also be controlled either completely or in parts [see GREENHOUSE TECHNOLOGIES for environmental control]. Specific to vertical farms, there are various setups that can occur.

Stacked horizontal growing platforms are one option for vertical farms. There can be rotating levels, which are costly and financially unproven, but allow each level of crop access to sunlight in one story buildings. There can also be non-rotating levels which are more affordable and require electrical lighting at each level. Finally, each level can be isolated from the surrounding levels. This is best for insect/disease control in controlled environments, yet it requires complex environmental control systems (lighting, air flow, water flow) over each section. Crops can also be grown on vertical surfaces such as balconies, sides of buildings, or around cylindrical housing units. Balconies and building sides are not suited for commercial use, but cylindrical housing units can be used commercially. In general, stacked horizontal units are most common in the commercial industry.[33]

FIGURE 9 TYPES OF VERTICAL FARMING

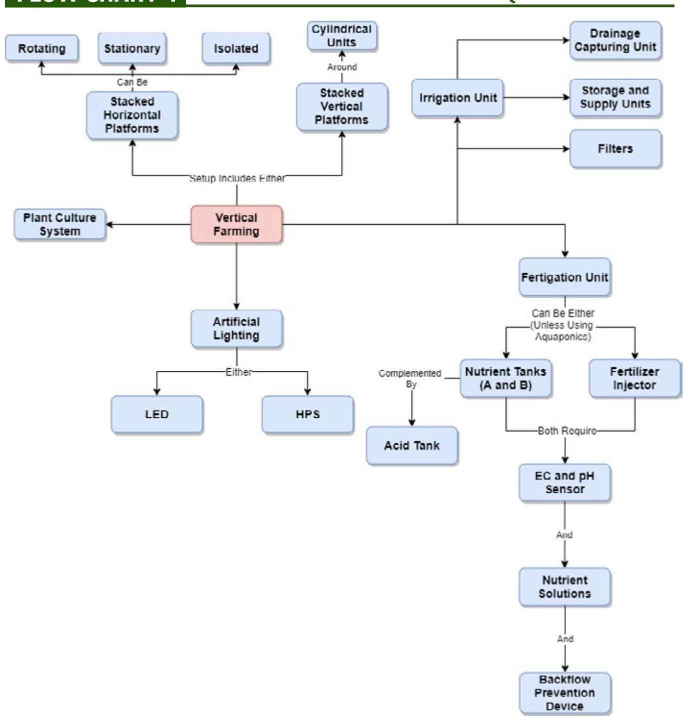
Beacham, Andrew M, et al. *Vertical Farming: A Summary of Approaches to Growing Skywards.* Taylor & Francis, The Journal of Horticultural Science and Biotechnology, 14 Feb. 2019, www.tandfonline.com/doi/full/10.1080/14620316.2019.1574214



(A, B, C - horizontal, A - rotating, B - stationary, C - isolated sections, D - stacked horizontal surfaces, E - building sides or vertical surface, F - cylindrical unit)

Additionally, artificial lighting is required even within a glass greenhouse setting; the sunlight coming into the structure of a glass greenhouse does not uniformly light the plants as they are stacked underneath one another in levels.[34] Light emitting diodes (LEDs) are one option to provide light by electrical power. They have a long life, low price, are efficient in energy compared to traditional horticultural lighting, and capable of targeting particular light wavelengths to manage the photoperiod and control various plant characteristics.[35] High pressure sodium (HPS) lights are slightly less efficient than LEDs and they provide intense heat that can damage the plants.[36]

FLOW CHART 4 VERTICAL FARMING TECHNOLOGY REQUIREMENTS



33 Beacham, Andrew M, et al. *Vertical Farming: A Summary of Approaches to Growing Skywards*. Taylor & Francis, The Journal of Horticultural Science and Biotechnology, 14 Feb. 2019, www.tandfonline.com/doi/full/10.1080/14620316.2019.1574214.

34 *Vertical Farming vs. Greenhouse Farming*. Growcer, 23 May 2019.

35 Kalantari, Fatemeh & Mohd tahir, Osman & Mahmoudi Lahijani, Ahmad & Kalantari, Shahaboddin. (2017). *A Review of Vertical Farming Technology: A Guide for Implementation of Building Integrated Agriculture in Cities.* Advanced Engineering Forum.

36 Pickens, Jeremy M, et al. *Greenhouse Crops and Cropping Systems for Commercial Aquaponics.* Southern Regional Aquaculture Center, United Stated Department of Agriculture, Aug. 2016.

AQUAPONICS TECHNOLOGY

Aquaponics is the combination of aquaculture - the farming of aquatic species - with hydroponics - soilless crop production. At its most basic, an aquaponic system extracts water from tanks where fish inhabit to fertilize hydroponically grown plants. In a closed cycle system, the water is returned to the fish after passing through the plants' roots. This process reduces both the use of mineral resources as well as the water input.[37] An aquaponics system requires a fish system, hydroponic system, water transport materials, and general technology,

With regards to fish, one must consider tanks, type of fish, fish food, and how to remove waste from the fish water. When choosing fish, important considerations are their adaptability, resilience, diets, and breeding habits.[38] Tilapia are the most common in this type of system as they easily adapt to various water qualities (such as varying pH, low DO), have an omnivorous diet (meaning they can live with other fish), are easy to breed, and breed every four to six weeks. However, they do require warm water temperatures and are not the most popular fish on the market. Other common fish include ornamental fish, catfish, and perch.[39]

Fish tanks should be made of plastic that is UV resistant, or fiberglass. It is also common to use animal stock tanks. The tanks should be round with a flat bottom - for ease of circulation - and should be light in color for ease of viewing the fish and reflection of sunlight to maintain a constant water temperature. They should not be black because fish do require minimal sunlight. The tanks also need to be covered with cloth, tarps, woven palm fronds, or plastic lids to prevent algae growth. For removing waste, a clarifier is used to drain the sludge from the fish water and a mechanical filter to separate solids and fish waste from the circulating water.[40] Finally, a biological filter must be used to convert the ammonia waste produced by the fish into nitrite and then nitrate.[41] With regards to the plant hydroponic system, a DWC or NFT system is recommended for commercial use. Ebb and flow can be used for smaller scale operations but are generally most useful for germination and seedlings.

With an ebb and flow system, grow beds are used and covered with a substrate.[42] These beds can be made from plastic, fiberglass, or a wooden frame. The biggest requirement is that they are water-tight, which can be achieved through rubber or polyethylene sheeting.[43] The substrate is chosen based on characteristics such as plant support ability, lifespan, water retention, ability to host bacteria, and neutrality. Hydroton is a very common media made from expanded clay that is pH neutral and buoyant.[44] Volcanic gravel is another medium that has a long lifespan and is excellent for plant support.

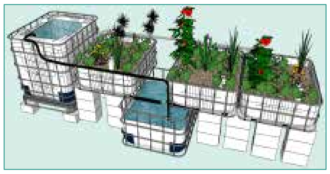
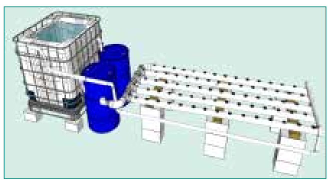
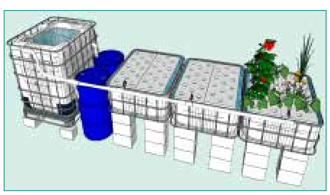
To elaborate, aquaponics requires a biofilter to convert ammonia to nitrite and nitrate. There can either be a media acting as a biofilter with a low pH and high surface area for nitrifying bacteria to adhere to, or a separate biofilter mechanism. Unfortunately, in DWC and NFT systems, there is generally no place in the beds for a biofilter media. Therefore, bio-balls or filter media blocks can be used - instead of substances like hydroton or lava rock - in a separate system from which the water is transported into the hydroponic system. In a commercial setting, you generally want a separate biofilter.[45]

With regards to the systems themselves, a DWC system can be made out of wood or concrete canals, while an NFT system is generally made out of PVC pipe or hydroponic pipes.[46] For DWC, the system needs to be made waterproof in a similar fashion to the grow beds. A mechanical filter is also necessary.

37 König, Bettina, et al. *Analysis of Aquaponics as an Emerging Technological Innovation System.* Journal of Cleaner Production, vol. 180, 2018, pp. 232–243., doi:10.1016/j.jclepro.2018.01.037.
38 Storey, Nate. *Best Fish for Aquaponics. uponics.* 12 June 2019.
39 Love, David C, et al. *Commercial Aquaponics Production and Profitability: Findings from an International Survey.* Aquaculture, Elsevier, 28 Sept. 2014.
40, 43, 46 Somerville, Christopher. *Small-Scale Aquaponic Food Production: Integrated Fish and Plant Farming.* Food and Agriculture Organization of the United Nations, 2015.
41 Rorabaugh, Patricia A. *Introduction to Hydroponics and Controlled Environment Agriculture.* Revised July 2015.
42 Knaus, Ulrich, et al. *Coupled Aquaponics Systems.* Aquaponics Food Production Systems, by Harry W Palm, Springer International Publishing, 2019, pp. 163–199.
44 *Aquaponics 101* Part 2. Aquaponics 101, Aquaponics USA.
45 Tollefson, Stacy. *Aquaponics 2019*. PowerPoint. 13 Nov. 2019, Tucson, Controlled Environment Agriculture Center.

TABLE 2 COMPARISON OF HYDROPONIC SYSTEMS USED IN AQUAPONICS

Somerville, Christopher. *Small Scale Aquaponic Food Production: Integrated Fish and Plant Farming.* Food and Agriculture Organization of The United Nations, 2015. http://www.fao.org/3/a-i4021e.pdf

System type	Strengths	Weaknesses
Media bed units 	Simple and forgiving design Ideal for beginners Alternative/recycled parts can be used Tall fruiting vegetables are supported All types of plants can be grown Multiple irrigation techniques Many types of media can be used High aeration when using bell siphons Relatively low electrical energy Medium captures and mineralizes solids	Very heavy, depending on choice of media Media can be expensive Media can be unavailable Unwieldy at large scale Higher evaporation than NFT and DWC Labour-intensive to construct Flood-and-drain cycles require careful calculation of water volume Media can clog at high stocking density Plant transplanting is more labour-intensive as the media needs to be moved If water delivery is not uniform, plant performance may differ from bed to bed
NFT units 	More cost-effective than media beds on large scale Ideal for herbs and leafy green vegetables Minimal water loss by evaporation Light weight system Best method for rooftops Very simple harvesting methods Pipes spacing can be adjusted to suit different plants Well researched by commercial hydroponic ventures Smallest water volume required Minimal labour to plant and harvest	More complex filtration method Water pump and air pump are mandatory Cannot directly seed Low water volume magnifies water quality issues Increases variability in water temperature with stress on fish Water inlet pipes can easily clog Vulnerable to power outages
DWC units 	More cost-effective method than media beds on large scale Large water volume dampens changes in water quality Can withstand short interruptions in electricity Minimal water loss by evaporation Well researched by commercial hydroponic ventures Polystyrene rafts insulate water from heat losses/gains keeping constant temperatures Shifting rafts can facilitate planting and harvest Rafts provide biofilter surface area DWC canals can be fixed with plastic liners using almost any kind of wall (wood, steel frames, metal profiles) Can be used at multiple stocking densities	More complex filtration method Very heavy unit High dissolved oxygen required in the canal, and a more sophisticated air pump is required Plastic liners must be food-grade Polystyrene sheets are easily broken Tall plants are more difficult to support Large water volume increases humidity and the risk of fungal disease

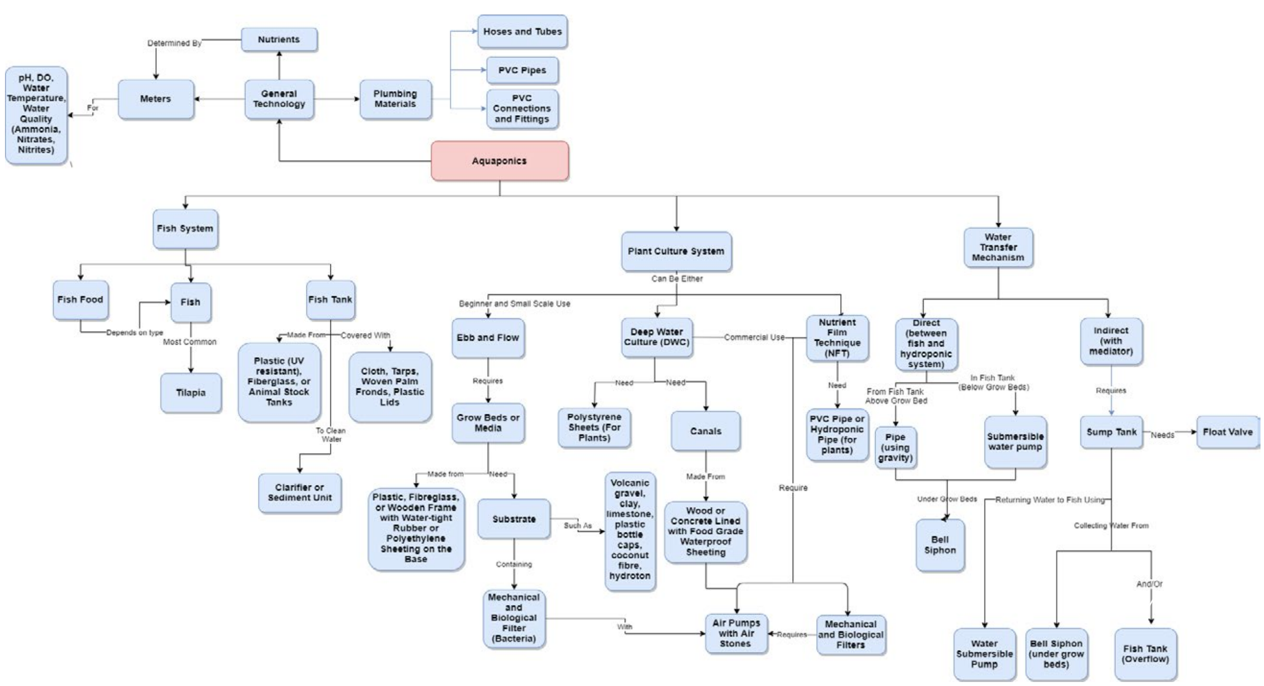
For transporting water, there are an abundance of options. One set-up is to have the fish tank below the grow beds. A siphon drain can be attached to the bottom of the beds, allowing water to drain by gravity into the fish tank (through a pipe system). A submersible water pump can be used to transport the water from the fish tanks to the grow beds.[47] If the fish tank is above the grow beds, gravity can be used to transport water through pipes to the grow beds, which can drain using a bell siphon. A pump can bring water back into the fish tank.

With large scale operations, having an intermediate tank is required. This is known as a sump tank. A sump tank can be used to collect overflow water from the fish tank, collect water from the hydroponic system directly from the bell siphon, and/or to provide water to each component. Mainly, a sump tank is used to prevent large fluctuations in the water levels of the fish tank which can cause stress. A float valve is necessary for the sump tank; float valves bring in outside water so the water level remains at a specific height despite evapotranspiration.[48] A sump tank is also useful in providing a place to add in acids, nutrients, or any other necessary components.[49]

With regards to general technology, sensors and plumbing materials are required. Characteristics including pH, dissolved oxygen, water temperature, and water quality (such as ammonia, nitrate, and nitrite presence) must be observed. Each of these components is vital for fish, plants, and bacteria survival. A total dissolved solids meter assists in understanding the effectiveness of filters and quality of water.[50] Plumbing materials include PVC pipe, PVC cement, Teflon tape, and silicone sealant.

Aquaponics does have many challenges. First, the system requires expertise in both plant and fish maintenance. Additionally, it is difficult to make money on both plants and fish; one must be chosen to capitalize and focus on. With regards to the water, fish and starting microbes prefer a pH of around 7 to 8, while plants like a pH of 6 to 7. Therefore, one must balance the pH between the two main areas. Finally, the chemicals being put in the water to control parameters or biological pests must be fish safe. For example, as the system matures the pH calms down from its extensively high pH values that occur in the first year. Consequently, the system requires base to be added in order to bring the pH up. Traditional hydroponic acids cannot be added; B-Hydroxycarboxylic acid is an example of a fish safe acid that can be added to an aquaponics system.[51]

FLOW CHART 5 AQUAPONIC TECHNOLOGY REQUIREMENTS



47, 50 *Aquaponics 101* Part 2. Aquaponics 101, Aquaponics USA.

48 Somerville, Christopher. *Small-Scale Aquaponic Food Production: Integrated Fish and Plant Farming*. Food and Agriculture Organization of the United Nations, 2015.

49, 51 Tollefson, Stacy. *Aquaponics 2019*. PowerPoint. 13 Nov. 2019, Tucson, Controlled Environment Agriculture Center.

CROP OPTIMAL CONDITIONS

NUTRIENTS

All crops require nutrients. There are the three basic nutrients: carbon, oxygen, and hydrogen. There are six macronutrients: nitrogen, phosphorous, potassium, calcium, magnesium, and sulfur. Then, there are the seven micronutrients: iron, manganese, boron, zinc, copper, molybdenum, and chlorine.[52] These nutrients tend to change in amount during various stages of growth (germination, seedlings, transplant, and then general growth until harvest). They also vary depending on the crop type. There is no optimal concentration of each nutrient because concentrations depend on desired characteristics from crop growth. Below is a table showcasing various authors' ideas regarding the concentration of essential nutrients[53] for general hydroponic crops.

TABLE 3 ESSENTIAL NUTRIENTS FOR HYDROPONIC GROWTH

Libia I. Trejo-Téllez and Fernando C. Gómez-Merino. *Nutrient Solutions for Hydroponic Systems, Hydroponics - A Standard Methodology for Plant Biological Researches*,2012. Dr. Toshiki Asao (Ed.) ISBN: 978- 953-51-0386-8, InTech.

Nutrient	Hoagland & Arnon (1938)	Hewitt (1966)	Cooper (1979)	Steiner (1984)
	mg L^{-1}			
N	210	168	200-236	168
P	31	41	60	31
K	234	156	300	273
Ca	160	160	170-185	180
Mg	34	36	50	48
S	64	48	68	336
Fe	2.5	2.8	12	2-4
Cu	0.02	0.064	0.1	0.02
Zn	0.05	0.065	0.1	0.11
Mn	0.5	0.54	2.0	0.62
B	0.5	0.54	0.3	0.44
Mo	0.01	0.04	0.2	Not considered

52 Rorabaugh, Patricia A. *Introduction to Hydroponics and Controlled Environment Agriculture.* Revised July 2015.

53 Libia, Trejo-Téllez and Fernando C. Gómez-Merino (2012). *Nutrient Solutions for Hydroponic Systems, Hydroponics - A Standard Methodology for Plant Biological Researches.* Dr. Toshiki Asao (Ed.), ISBN: 978- 953-51-0386-8, InTech.

TABLE 4 FRUITING CROP (TOMATOES) OPTIMAL ENVIRONMENTAL CONDITIONS

	Day / Night	Cloudy	Sunny
CO_2 (ppm)		400-1500	
Daily Light Index DLI (mol/m^2/day)		Seedlings: 6-8 Mature: 22 to 30 20 (minimum) - 30 (optimal) *Fruiting crops require at least 4-6 hours of darkness daily*	
Dissolved Oxygen (DO) (ppm)		5-7	
EC		1.8-5.0 mS or 1400-3500 ppm	
Fertigation and Irrigation	2-3 L water per day per plant	10 - 20% overwater	30-50% overwater
Humidity (%)		60-75	
pH		5.5 - 6.3	
Temperature (°F)	Day: 70-82 Night: 62-64	Closer to lower end	Closer to higher end

TABLE 5 LEAFY GREEN CROP OPTIMAL ENVIRONMENTAL CONDITIONS

	Day / Night	Cloudy	Sunny
CO_2 (ppm)		Ambient - Seedling and germination stage 400 - Production stage to week 1 650ppm - Week 2 850ppm - Week 3 to week 4	
Daily Light Index DLI (mol/m^2/day)		Butterhead lettuce: 14-18 Seedlings: 6-8 Lettuce in general: 16 - 18	
Dissolved Oxygen (DO) (ppm)		6-8	
EC		1.8-2.5 mS	
Fertigation and Irrigation		Constant flow (unless using aeroponic system)	
Humidity (%)		50-70	
Lighting		18 hr/day photoperiod during germination (once they pop up) 16 - 18 hour/day photoperiod for seedling stage to harvest	
pH		5.5-6.5	
Temperature (°F)	70 for germination Day - 75.2 for seedling to harvest Night - 66.2 for seedlings to harvest 70-75°F for root zone	Closer to lower end	Closer to higher end 70-75°F for root zone

TABLE 6 MICROGREENS OPTIMAL ENVIRONMENTAL CONDITIONS

	Day / Night	Cloudy	Sunny
CO_2 (ppm)	800-1200		
Daily Light Index DLI (mol/m^2/day)	6 min to 12 (ideal) *See image below*		
Dissolved Oxygen (DO) (ppm)	6-8		
EC EC (mS/cm)	0.5 to 1.5		
Fertigation and Irrigation	Constant flow (unless using aeroponic system)		
Humidity (%)	20-30 for softer touch 50 for crispier, fresher taste		
Lighting	18 hr/day photoperiod during germination (once they pop up) 16 - 18 hour/day photoperiod for seedling stage to harvest Some microgreens require a blackout period for the first few days (4-5 days after seeding)		
pH	6		
Temperature (°F)	60 to 75		

POPULAR CROPS

HYDROPONICS

In general, popular consumer crops such as leafy greens, herbs, and vining plants are grown commercially in hydroponics. Some of the most common commercially grown crops are[54]:

- Vine Crops
  - Tomatoes
  - Cucumbers
  - Peppers
- Herbs or Microgreens
  - Basil
  - Watercress
  - Dill
  - Oregano
  - Bok Choi
- Leafy Greens
  - Lettuce
  - Kale
  - Spinach

54 Martin, Melanie J. *The Best Plants for Hydroponic Greenhouses. Home Guides* | SF Gate, 17 Dec. 2018.

CROP TECHNOLOGY REQUIREMENTS

FRUITING CROP (TOMATOES) | GREENHOUSE HYDROPONICS

To grow tomatoes on the vine, there must be a support system in place. Generally, a high wire or trellis system is used. The wire should be able to hold around three tons for 600 plants (or 10 lbs per plant assuming one ton is 2,000 lbs). The vines are strung up towards the wire with string and clipped to the string.[55] Tomato seedlings need to be grown separately from the overall system because they require a higher humidity at first. They are generally grown in propagation blocks of substrate in an ebb and flow system.[56] Tomatoes can then be supplied with irrigation and fertigation using any of the systems provided in HYDROPONICS Technology.

The most commercially implemented hydroponic system for vining crops (such as tomatoes, cucumbers, and peppers) cultivation is drip irrigation. Drip irrigation is used to provide fertigation and irrigation to the tomatoes being grown in either substrate slabs or substrate filled buckets. There need to be grow benches set up at an angle so the water can drain out at the end. On top of the benches sit bags with substrate for the tomato roots to grow in. Additionally, these benches should be placed underneath the high wire support system with wires at least two feet apart in a double row system. 2.5-3 plants per meter squared is the generic spacing for tomato plants.[57]

The greenhouse floor should be covered with white polythene to suppress weeds and increase the light being reflected back up to the crops. The substrate slabs (if using drip irrigation) should be placed under polystyrene for insulation if the floor is not heated.[58] The image below shows tomatoes being strung using a trellis system. Their roots are grown into substrate blocks placed in larger substrate bags. The bags are positioned on benches with a drip irrigation system leading to each separate substrate block. The bags and floor are covered with a white covering. Using white tubing and covering is done to prevent the water and the media from heating up (conserving dissolved oxygen).

FIGURE 10 PEPPERS AND TOMATOES IN TRELLIS SYSTEM WITH DRIP IRRIGATION FOR COMMERCIAL HYDROPONIC GREENHOUSES

Lecuona, Antonius. *Trellising hydroponically grown peppers – secret to growth optimization.* Commercial Hydroponic Farming. July 28, 2013. https://www.commercial-hydroponic-farming.com/trellising-hydroponically-grown-peppers/

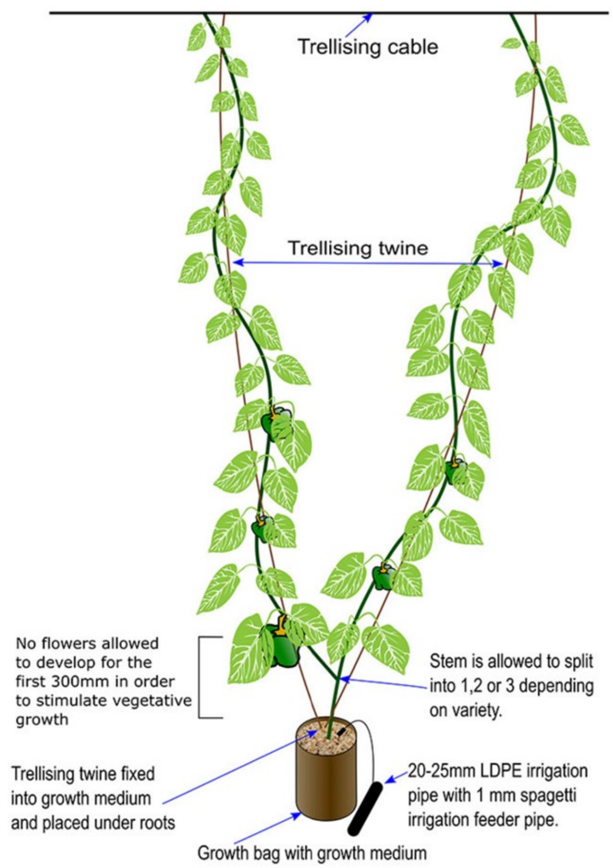


FIGURE 11 TOMATOES USING DRIP IRRIGATION IN COMMERCIAL GREENHOUSE

Hortidaily. https://www.hortidaily.com/

55, 58 Langenhoven, Petrus. *Hydroponic Tomato Production in Soilless Culture*. Presentation. Indiana Horticulture Congress, 13 Feb. 2018.
56 Morgan, Lynette. *Hydroponic Tomatoes*. Greenhouse Production News, The Growing Edge Magazine, Oct. 2003.
57 Rorabaugh, Patricia A. *Introduction to Hydroponics and Controlled Environment Agriculture.* Revised July 2015.

FRUITING CROP (TOMATOES) | VERTICAL FARMING

With regards to the stacked trays technique for vertical farming, this is not a viable option for tomatoes. As previously stated, tomatoes grow vertically upward. Therefore, the stacked trays would be inhibiting for the crops. Commercially, tomatoes are grown using greenhouse hydroponics.

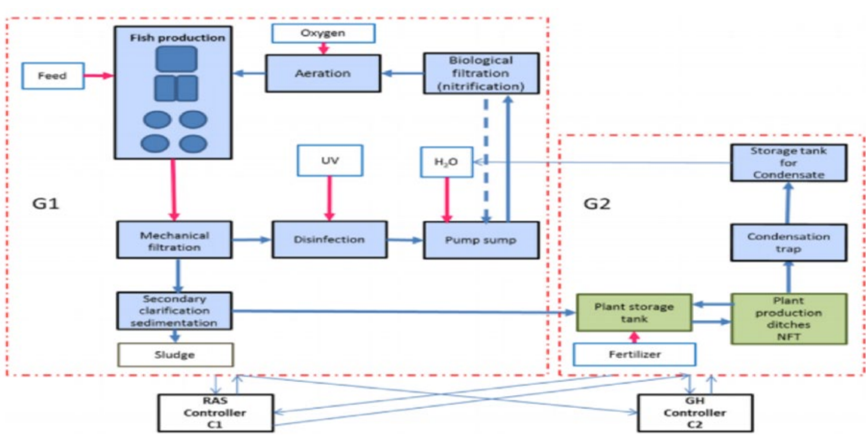
FRUITING CROP (TOMATOES) | AQUAPONICS

An example of aquaponic tomato production[59] was done using Nile Tilapia (Oreochromis niloticus) and tomatoes (Solanum lycopersicon) in a double recirculating aquaponic system (INAPRO aquaponic system based on ASTAF-PRO technology). The INAPRO system is a double recirculating system containing two subsystems, a recirculating aquaculture system (RAS), and a recirculating hydroponics unit all within a greenhouse. Fish water containing nutrients is delivered to the hydroponic reservoir to act as fertilizer; the transpired water from the plants is collected and returned to the RAS to minimize overall water consumption by the process. Optimum conditions can be set up in each subsystem to keep the systems independent in case there are issues in the future. Aquaponic simulation software can save time and money on optimizing pilot-scale systems.

On the hydroponics side, the size of the plants determines the total water and nutrient uptake, as well as the production of condensate for reuse in the RAS. On the RAS side, the waste produced by the fish and the required feed depends on the fish species, age, and size. A biological filter performs nitrification to convert ammonium to nitrate.

FIGURE 12 AQUAPONIC WATER FLOW

Karimanzira, Divas, et al. Aquacultural Engineering, vol. 75, Nov. 2016, pp. 29–45. ScienceDirect. https://doi.org/10.1016/j.aquaeng.2016.10.004



Tilapia initial conditions:

- 1329 tilapia fish were in a 40 m3 tank
- The tank was operated as a CSTR with Qin=out=4.5 m3/s
- The operating temperature of the tilapia tank was 28 degrees Celsius
- The tilapia fish were fed twice a day
- Initial weight of one fish is 10 g
- The tilapia fish were harvested after 8760 hours, or one year

Tilapia results:

- The minimum, optimal, and maximum water temperature for tilapia production was 15, 33, and 41 degrees Celsius, respectively
- The maximum and critical concentration of ammonia in the water for tilapia production were 1.4 and 0.6 mg/L, respectively
- Nile tilapia can use atmospheric oxygen when the D.O. drops below 1 mg/L
- The critical and minimum concentrations of D.O. for Nile tilapia are 1.0 and 0.3 mg/L, respectively
- The average weight of one fish after harvest is about 770 g
- Mortality rate of fish per production cycle is 14%
- The maximum and critical BOD concentrations in the tank water were 20 and 40 g/L, respectively

Tomato initial conditions:

- One plant per m2
- No other information on the initial conditions or results for tomatoes were given

59 Karimanzira, Divas, et al. *Aquacultural Engineering, vol. 75,* Nov. 2016, pp. 29–45. ScienceDirect, doi:https://doi.org/10.1016/j.aquaeng.2016.10.004.

LEAFY GREENS | GREENHOUSE HYDROPONICS

When growing lettuce hydroponically, aeroponics, NFT, and DWC systems are the most commonly used with NFT being the most common.[60] In general, there needs to be an ebb and flow system for the seedling stages.[61] The technology requirements are mainly described in the NFT and DWC sections. Specifically, for NFT systems, lettuce should have a trough width of about 4-8 cm. Additionally, the water flow rate should be between 3 and 8 L/m^2/h.[62]

LEAFY GREENS | VERTICAL FARMING

Vertical farming is a highly common practice with regards to lettuce production. There is an abundance of ways to execute such a practice. AeroFarms has successfully grown lettuce in vertical racks using aeroponics [FIGURE 8]. NFT and DWC systems can also be adapted in vertical production. When implementing NFT systems, they either need to be vertical, or placed on horizontally rotating racks. The horizontal rotating racks or conveyor rotation method is demonstrated in this video (https://youtu.be/TOspe6crq3s) from Cubic Farms. Additionally, this rotation system allows for a decrease in light and energy requirements because only one section of light is required at the top rather than on each stacked horizontal section. On the other hand, ZipGrow has implemented a vertical tower NFT system. The issue with this type of system is ensuring that all plants get equal light on the top and bottom.[63] Bowery has implemented the DWC system in horizontally stacked containers. Each section has its own set of LEDs to provide uniform lighting (Vyas).

FIGURE 13 LETTUCE IN AN NFT SYSTEM

© Darwel/Getting Images

FIGURE 14 BOWERY FARMS IMPLEMENTING A HORIZONTAL STATIONARY DWC VERTICAL FARMING METHOD

© Bowery. boweryfarming.com

Finally, Sky Greens implements a hydraulic driven farm with horizontally stacked, rotating systems that rotate throughout the day. The plants on the top receive light coming from the sun emitting through the top of the greenhouse. Alternatively, the plants at the bottom receive water.[64] The issue with rotating systems is that if the rotation breaks, there must be a backup way to provide light or nutrients to the plants.

FIGURE 15 SKY GREENS USING HORIZONTALLY STACKED ROTATING VERTICAL SYSTEMS

Sky Greens. *Rise of the Vertical Farm*. Retrieved from https://www.farmmeetstable.com/en/pioneering-new-technology/2018/rise-of-the-vertical-farm

Overall, there are an abundance of methods that can be used to grow lettuce vertically. While there is no commonly implemented method, it appears as though using horizontally stacked sections is the most efficient. Using closed or open circulation, or rotation methods for sunlight usage or LEDs, is completely up to the producer depending on how efficient and sustainable they want to be.[65]

60 Parkell, Natalie B, et al. *An Overview of Lettuce Production Systems and Cultivars Used in Hydroponics and Protected Culture in Florida*. IFAS Extension, University of Florida, Mar. 2015.
61 Brechner, Melissa, and A.J. Both. *Hydroponic Lettuce Handbook*. Cornell University CEA Program, 2013.
62 *13.2.2.3 Nutrient Film Technique*. Soilless Culture: Theory and Practice, by Michael Raviv et al., Academic Press, an Imprint of Elsevier, 2019, pp. 587–635.
63, 64, 65 Vyas, Kashyap. 13 *Vertical Farming Innovations That Could Revolutionize Agriculture.* Interesting Engineering, Interesting Engineering, 24 Sept. 2018.

LEAFY GREENS | AQUAPONICS

One pilot-scale system at the University of Hawaii at Manoa[66] utilized shallow wooden trays lined with plastic and filled with water. Lettuce plantlets were placed in "net pots" that were placed in holes in Styrofoam panels suspended above the growing area so the lettuce roots could obtain nutrients from the water. The effluent water from the fish tank and chemical fertilizers provided the necessary nutrients to the plants, and the water from the lettuce trays was recycled back into the fish tank before a new batch of fish tank effluent entered the tray. Air pumps were necessary to increase dissolved oxygen levels in the tank and to prevent denitrification.

Each tray produced 48 heads of lettuce every 5-6 weeks. Below are the specific material and construction properties of the system:

- The tray bottom was a ¾-inch thick, 4x8-ft high density overlay plywood sheet
- The sides were constructed using 2x4s, two 8-ft and two 4-ft pieces were attached to the outside of the plywood bottom
    - The plywood was connected to the 2x4 walls using 2-inch #8 stainless steel screws spaced out 16 inches from one another
    - Two 3-inch #10 stainless steel screws were installed in the corner to attach the sides to one another
    - The long and short walls were placed 1 ½ inches away from the edge of the plywood sheet to prevent splitting of the plywood using the screws
- The completed tray should be placed on six hollow concrete blocks (6x8x16-inch) to achieve a height of one or two blocks high
- A 6x10-ft liner was created from a 20-ft wide roll of 6-mil polyethylene plastic
- Polystyrene panels (four per tray, 2x4-feet, 2-lb density) with twelve holes drilled into the panel using a 2-inch hole-saw drill bit were used to hold the net pots
    - Hole spacing used staggered rows
    - 4-inches away from the edge of the panel
    - 12-inches apart within the rows
    - 2-inch diameter holes
    - 8-inches apart on-center
- 4-inch plastic flowerpots were used as the net pots
    - Water-absorbing, foam plant-propagation cubes were used to sprout the lettuce from the seed over a germination period of two-weeks before transferring the sprout to the net pots
    - The trays were filled with a water level high enough to reach the bottom of the net pots
    - The lettuce heads should be ready to harvest after 5-6 weeks of transferring the foam cubes to the net pots
- For the aquaculture tank, a 2.6-gallon submerged biofilter was placed in the tank to convert ammonia into nitrate so the fish are not poisoned, and the lettuce plants can utilize nitrate
    - The West Virginia University Aquaculture Facility[67] utilized a 2.5-cm ball valve and a 5-cm diameter drainpipe in their aquaponics system to independently control the water level in the aquaponic channels

66 Ako, Harry, et al. *Small-Scale Lettuce Production with Hydroponics or Aquaponics.* Sustainable Agriculture, October 2009, University of Hawai'i at Manoa College of Tropical Agriculture and Human Resources Department of Molecular Biosciences and Bioengineering.

67 Buzby, Karen M, and Lian-Shin Lin. *Scaling Aquaponic Systems: Balancing Plant Uptake with Fish Output.* Aquacultural Engineering, vol. 63, Dec. 2014, pp. 39–44. ScienceDirect, doi:https://doi.org/10.1016/j.aquaeng.2014.09.002.

MICROGREENS AND AQUAPONICS

Mizuna and rocket salad were used as short-cycle vegetable crops in an NFT system to observe how the aquaponic nutrient composition impacted microgreens production. Microgreens have a shorter growth cycle, and therefore, may be able to better adapt to the changes in the aquaponic water because the seed stores additional nutrients, like a reservoir, in case the aquaponic water is lacking in nutrients.

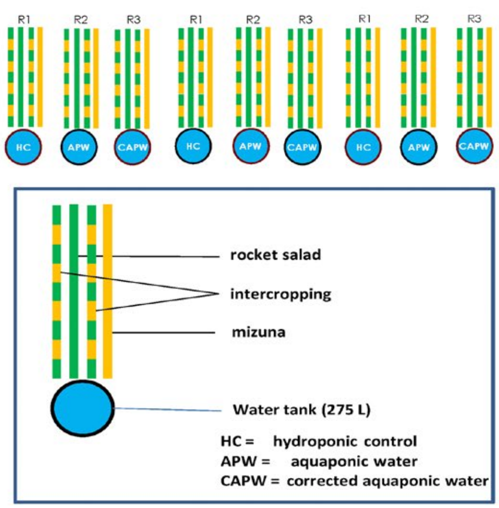
Conditions:

- Water tank contains 1.65 m3 of water
- Fish tank with a volume of 3 m3 150 pangasius fish with an average weight of 300 g per fish
- Four NFT channels in each system utilizing high-density sowing (3000 plants per m2)
  - The seeds were sown using a self-constructed sowing device on a synthetic carpet (80% viscose and 20% polyester—Growfelt, UK)
  - During the crop cycle, the transpired water was replaced every second day with fresh water and the amount of water added was recorded.
- Three nutrient solutions:
  - APW – aquaponics water the contained nitrate nitrogen
  - CAPQ – aquaponic water that is supplemented with P, K, micro, and macro nutrients
  - HC – a hydroponic control that has the same content of nitric nitrogen as seen in the fish water & the same nutrients as the supplemented fish water

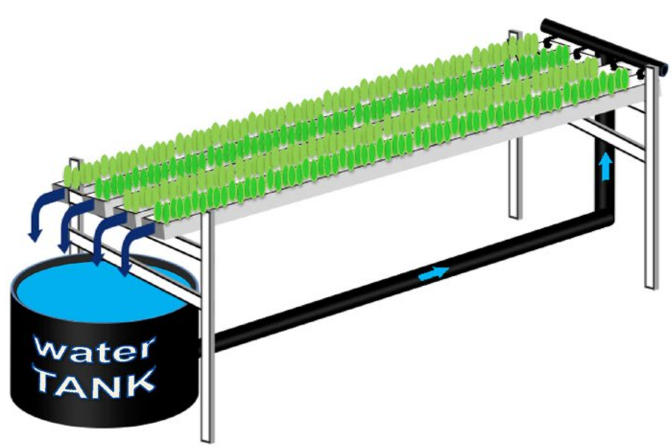
The results of this study showed that microgreens growing in the HC and CAPW solution always exhibited higher growth than those grown in the APW solution.

FIGURE 16 AQUAPONICS SETUP FOR MICROGREENS

Nicoletto, Carlos, et al. *Extension of Aquaponic Water Use for NFT Baby-Leaf Production: Mizuna and Rocket Salad.* Agronomy, 17 May 2018. MDPI, https://www.mdpi.com/2073-4395/8/5/75



(**A**) overview of the experimental design



(**B**) single cultivation mesocosms