Growing Up:
Greenhouse Designs for Urban Spaces

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Introduction

One of the biggest problems the world faces is the potential for a food shortage. As the population increases, food production must increase at a matching pace. Combined with an ever changing climate that can damage crops through droughts, increased temperatures, or dangerous storms, not all crops will survive to be harvested. Currently, about 55 percent of the human population lives in cities or urban areas, meaning that their food must be transported from agricultural areas around the world (United Nations, 2018). Likewise, "An estimated 55 percent of the world's crops are used for human consumption, but roughly one-third of that food is wasted annually. Roughly 1.3 billion tons of food is wasted either due to not being used or being lost" (E. Cassidy et al., 2013). In some countries, such as the United States, some food is even wasted because it does not look desirable and is thus not put onto store shelves. Partially due to this food waste, it is estimated that by the year 2050, we will need more farmland than is currently available to feed the entire world's population (E. Cassidy et al., 2013). To help negate this problem, we need to figure out current solutions to future problems, and one such solution is to find more efficient methods for growing crops.

The idea of greenhouses has existed since the Roman Empire, with the first known structure being described by Pliny the Elder as, "frames glazed with mirror-stone" (Pliny the Elder, N.D.). However, as with most forms of architecture, as humans have advanced so has our understanding of how things work. This has led to advancements in building materials, growing methods, and building design, which could all be applied to modern greenhouses to create facilities that are more efficient than ever before. This capstone will investigate how to update these greenhouses to begin growing more food in smaller spaces by combining all of these technological advancements. The outcome will help create efficient greenhouses while considering climate and available space. Different crops require different heat values and UV indices to grow, and the local conditions must be considered as well. For example, if corn requires a soil temperature of around 50° F, and 10 hours of sunlight a day, and material A provides these conditions than it would be appropriate for the crop. However, if the greenhouse is to be constructed in a cold climate with only 8 hours of sunlight a day, would it still be appropriate for construction due to its insulation level and lack of light?

Furthermore, how does the shape and size of the greenhouse and enclosure influence conditions? Can a single room greenhouse grow crops with different requirements, or do we need to split the enclosure into sections? Finally, how can greenhouse design incorporate tiered planting, aquaponics, and vertical gardens to be more efficient at production?

These questions will help guide this capstone and will be answered through a case study design. With the growing number of people living in cities, these methods will allow for more crops to be grown locally in a smaller area. These changes could also lead to a rise in urban agriculture, either through in-home gardens or communal gardens. With green skyscrapers being built in many growing metropolitan areas, this rise for "vertical forests" has already begun, but if we can make things even more efficient, perhaps someday we can negate the need for farmland. Even if we can only reduce our dependence on farmland and long-distance food transportation, perhaps we can make significant strides in delaying a food shortage until we can find a more permanent solution for the betterment of humanity.

Literature Review

A Brief History

The precursor structure that would lead to modern greenhouses was built sometime during the First Century AD in the Roman Empire. Described by Pliny the Elder in his book *The Natural History* written sometime between 77 and 79 AD, these early systems were used to grow early cucumbers for Emperor Tiberius. "…he had raised beds made in frames upon wheels, by means of which the cucumbers were moved and exposed to the full heat of the sun; while, in winter, they were withdrawn, and placed under the protection of frames glazed with mirror-stone." (Pliny the Elder, unknown) While this is the first known structure specifically utilized to grow crops, it is still far removed from what we have today.

The next big leap in greenhouses was first described in a seemingly odd place, a cookbook. *Sanga Yorok*, a Korean cookbook from 1459, was written by the Korean Royal family's doctor, Jeon Soon. "I will build a house, but I will make it big and small. I build a wall on three sides and put grease paper on it, and on the southern side I put a sheet of oil on it. Put out the balls, treat them well so that they do not smoke, build up a half-height of soil on the ondol, and plant spring vegetables. If the weather is very cool, make sure to cover it with a thick coat and remove it immediately if the weather is released. Sprinkle water every day to make dew always in the room, make sure that the mild aura always dries up and the soil does not dry, and you should walk the kettle on the wall and warm the room with the steam of the pot when it is lit in the morning and evening." (Jeon Soon, 1459) This oiled paper was a staple of farming on the Korean peninsula for centuries after this book was written, until the introduction of vinyl paper. The ondol refers to the traditional Korean method of heated floors. These were created by raising the floor off the ground to create a void underneath. Then a stove or furnace would be built at one end with a chimney on the opposite side. Fires would be built in the furnace, and the draft would blow the heat and smoke underneath the floor and out the chimney. Using this method allowed the soil beds in the garden to have a sustained heat throughout the frozen winter months.

While greenhouses had been around since Rome, the next instance of them returning to Europe was seen during the 17th century in the Netherlands and England. One of the earliest examples of these is Chelsea Physic Garden in England, which was built in 1681. This garden is still open today and was the first stove heated greenhouse in England. This was a great step in the right direction as many of these early greenhouses had no great way of maintaining heat during the winter months due to their scale, which was often large enough to grow millions of crops annually. The Chelsea Physic Garden occupied four acres of land and was established by Apothecaries to grow medicinal plants year-round. Its uses of an enclosed area warmed by a stove allowed for crops from many warmer climates, including South America and the East and West Indies, to be grown in the relatively cool climate of England. (Unknown Author, 2002) Another significant contribution of the Garden was, under the direction of Philip Miller, plants from all around the world were exchanged. “In a reign of almost fifty years, Philip Miller made Chelsea one of the foremost botanic gardens in the world, building an international network of contacts through which the range of plants was greatly extended and making himself the acknowledged authority on the requirements of innumerable novelties then flooding into Britain from distant parts of the world” (Sue Minter, 2000). This idea of exchanging crops and the knowledge to maintain them, began allowing for the creation of public gardens around the world that housed wild and exotic foliage, sparking public interest in Botany.

From there, the first example of a “modern” greenhouse was built by Charles Lucien Bonaparte in Leiden Holland. A French botanist, Bonaparte built this greenhouse in the 1800s to grow medicinal plants normally found in the tropics. He accomplished this by linking glass panels together using metal joiners creating the house-like structure that many modern greenhouses resemble. This allowed the sunlight to enter the building, warming the plants, and insulating them from the cold by retaining the heat from the day-long into the night. It was also in this Victorian Era that greenhouses and observatories became truly popular, especially with wealthy families and universities who often had these structures built on their land. For the families, these structures were often seen as a show of wealth, where the universities used them to study plants that could not be found locally.

Many countries found these structures to be increasingly useful, and some countries such as the Netherlands began investing heavily in greenhouses as a means of growing crops during the long winter months. The ability to maintain certain climates inside also allowed for crops that required a longer gestation period to be grown locally rather than being transported from far off lands. Once a need was found for these structures it began a trend of continuous innovation. From new designs, such as geodesic domes and gutter-connected systems, to new materials, such as polyethylene film and PVC, these structures are becoming more accessible daily.

New Materials

With a constant stream of innovative materials and technologies coming out, it makes sense to begin attempting to apply these to the idea of greenhouses. As we make every aspect of human existence ever more efficient, we also need to apply that to food growth, and one of the main places for this to be applied is in greenhouses where crops can grow throughout the year and in every climate imaginable. Many of these materials and technologies are already being utilized in other architectural aspects and need to be applied to a different standard to contribute.

The biggest item people think about when it comes to greenhouses is the exterior envelope, which has historically been made from glass or polyethylene, and some supportive structure, normally steel or PVC. These wrappings have worked well for a long time, but they do have certain limitations, namely that they cannot limit the amount of light that is entering the facility at any given time. Electrochromic glass has been around for a few decades now as one of the first patents was filed in 1997 by Mino Green from the United Kingdom (Patent Number 5,598,293), but it is just now becoming more widely used. Currently, this technology is used for privacy in office settings or for energy savings on buildings with large sun exposure. However, new research has demonstrated that electrochromic glass could be useful in greenhouse settings by controlling the amount of sunlight that enters certain areas of the facility- crops of varying exposure requirements can be mixed next to each other by adjusting the panels above them accordingly. A current study hosted by Swinburne University researchers, led by Baohua Jia and in partnership with Horticulture Innovation Australia, is currently being conducted across several nations and climates. Started in 2017, the research is continuing as of May 2019, and Professor Jia said, “The findings so far are very positive. The new technology is not widely used in greenhouses, and we hope to push renewable energy in a new way. Because plants are only light-sensitive to certain colors, the rest of the colors of light can be put to other uses, either by collecting the energy and generating electricity or converting energy to heat” (The Weekly Times, 2017; updated 2019). Because the study has not been fully published yet, the results are inconclusive but are promising. The statement about using the “unused colors of light” to generate heat is also an area of great interest. If the wasted light can be used, the plants do not need to generate power to sustain the systems of the greenhouse and efficiency increases.

One of the main problems with this idea historically has been the inclusion of Photovoltaic (PV) cells in the glass has created shadows over the plants, meaning that the greenhouse would have to supplement daylight. This is an issue that is being worked on, and according to research done by Bambara and Athienitis (2018), “Most prior work on PV greenhouses focuses on the development of novel semi-transparent photovoltaic (STPV) claddings. Various STPV technologies exist or are being developed. The STPV can provide partial shading by encapsulating uniformly distributed crystalline silicon PV cells between glazing materials or using thin-film PV modules.” By combining these two technologies, we could potentially create a closed system where the glazing uses PV cells to generate power, which will then be used to adjust the shading to match the needs of the crops inside. By adjusting the shading technology, we could potentially allow the light spectrum that plants need through, while simultaneously catching the light spectrum that can be used to generate energy.

Another exciting technology is the recent invention of self-sensing concrete. By adding conductive materials into the concrete, it allows for an electrical current to be applied to the concrete which can then sense structural defects and “heal” itself by using the current to vibrate filler material into these voids (Baoguo Han, et al., 2014). Because many portions of a greenhouse must be made using concrete, including footings for structural components, garden beds in multi-tiered systems, and some aquaponics systems, self-healing concrete could be useful by healing areas that normally could not be seen. In areas such as aquaponics troughs, this could alleviate the loss of water that would flow out of cracks in the foundation. In areas such as garden beds above ground level, this could help ensure that plants cannot find ways to weave their roots into cracks, further deteriorating the material. While this material has not been tested in gardening uses yet, the materials are similar enough that ensuring mineral absorption or chemical leaching that could be harmful to plant or fish life would be significantly reduced through known methods.

Two such filler conductive material to potentially be used in self-healing concrete is nanotubes or carbon tubes. These are extremely light and strong materials that have a variety of uses, including being a construction material. These could potentially be used in place of the steel or PVC joints that are used in the construction of the outer envelope of the greenhouses.

While they may not be ideal for holding glass panels yet, due to the cost of materials associated with creating larger calibers of tubes, they could be ideal for use in conjunction with much lighter polyethylene materials. However, due to their light nature, combined with their strength, these materials could be ideal for many other uses in plant growth, namely vertical gardening or tiered systems. These materials could be used to hang vine plants, such as tomatoes, melons, grapes, or strawberries, over long spans without the need for much bracing. They could also be used to create taller tiered systems that current PVC structures could not support. The issue with these systems, though is the cost of building these materials. While they may be more viable in the future, current production costs are higher than many private owners are willing to spend.

In that regard, there is the relatively cheap, and more renewable bioplastics and biocomposites. “Biobased plastics or simply bioplastics made from renewable resources can be naturally recycled by biological processes, thus conserving limited natural resources (fossil fuels) and reducing greenhouse gas emissions (CO2 neutral). Though bioplastics greatly interest many scientists and engineers throughout the world, they possess inferior properties compared to their synthetic counterparts. To improve the properties of bioplastics, polymer blends and composites are commonly investigated, which are called biocomposites” (James Couper et al. 2011). The main issue with these materials is their relative weakness, but with continuous research being put into them, they are beginning to catch up. So depending on the load being born by the material and the owner's desire for sustainability, they can still be used for many designs.

While these are just some of the new materials that have become commonplace in recent years, they are not the only ones available, nor are they the only way to improve greenhouse efficiency.

New Growing Methods

While it is a relatively new growing concept to be utilized by humans, aquaponics is a system that has existed in nature almost as long as plants and animals have existed together. “Aquaponics makes use of the natural processes of multiple organisms to reduce the number of materials needed to grow food. The basics of aquaponics are to raise fish in a tank that circulates water from that tank to a soilless medium where plants are grown. Bacteria growing on the medium convert ammonia and nitrate from fish waste in the water so that plants can absorb those nutrients to grow; the water is then returned to the fish tanks cleaned” (Cunningham, 2015). These tanks with the fish often have some fast-growing plants in them, such as duckweed. The most common fish being bred in these systems are tilapia and rock cod due to their ability to grow to edible sizes in larger groups in smaller areas. This idea of aquaponics is often seen as a combination of two systems, fisheries, and hydroponics. While large scale fisheries are something likely beyond the scale allowable for greenhouse production, hydroponics is a common practice already. “Hydroponics is referred to as the art of growing plants without the use of soil. Hydroponics is a form of soilless agriculture that is dependent on an aerated water-enriched nutrient solution, which is essential for the optimal growth of plants” (Muhammed, 2018). There are many different versions of hydroponics, but all of them have proven to be a useful system that allows many crops to be grown over a relatively smaller area because they can be planted vertically.

Another portion of these systems that makes them effective is the ability to grow vertically instead of spreading out horizontally. As noted earlier, it is estimated that farmland will run out by the year 2050 meaning it will no longer be possible to spread further to continue raising crops. This requires a shift to start growing crops vertically to provide enough room to feed the growing population. With over 7.5 billion people in the world at present, and growing, the amount of food necessary to sustain our global caloric intake is rising at an exponential rate. By creating vertical gardens, it is possible to raise more crops in a smaller horizontal space. While it may be impossible to grow some crops and plants vertically, such as trees or other tall plants (corn or wheat), there are still many plants that we can grow "up." Vined plants such as tomatoes, melons can be grown along a vertical pipe with support for the fruits. This could allow for multiple plants to be grown in a small area because they would no longer be climbing over each other and smothering one another while vying for resources. Other plants that grow as individuals or small clusters, such as carrots, potatoes, or herbs, can be planted in individual receptacles, which can then be hung along a wall or fence. Some plants can even be grown from a hanging position. By growing these plants from one central post and hanging them from a grid above the ground, space if freed to grow another crop. By combining the knowledge of what plants need what nutrients, light, and water, it is possible to grow "friendly" plants together, so they do not compete for the same resources.

Control Systems

With the exterior envelope in place, growing methods, and crops are chosen, there must be an understanding of how to control the interior environment to make it ideal. This is an area of technology that has garnered extensive research as interior climate control is critical to human comfort. Many of the same systems that are used in most buildings can be adapted to meet the needs of any greenhouse; it requires understanding the occupant's needs first. By utilizing the proper H/VAC system, humidity devices, fans, lights, sprinkler systems, and other comfort devices, it is possible to maintain the proper climate for the crops growing inside. If the building envelope maintains its seal, these systems should be able to generate a perfect balance. With new systems coming out almost daily, we are constantly heading towards more efficient and effective systems, as well.

However, monitoring all these systems, plus any water pumps, the electrochromic windows, and other systems installed can be a big task. That is where computer control systems come into play. When trying to solve the growing food shortage issue, the greenhouse will likely become massive, and so utilizing a monitoring system to ensure that all systems are meeting standards will be critical to continued food production. These systems could also limit the amount of unnecessary energy expenditure by shutting off systems when they do not need to be used. Similar to how these systems are being utilized in large office buildings for monitoring times of peak use or least use to shut off systems when they are not being utilized, they could perfect for ensuring best practices inside the greenhouse. This could also reduce the ultimate cost of crop production. As noted by Azaza Maher et al. (2016), "Hence, reducing the energy consumption of a greenhouse turns out of major importance to reduce the cost of production." While a specific program may be needed for each greenhouse, or even for individual areas of each structure, the idea remains the same regardless of size or shape. As these systems learn the needs of the crops being grown, they can slowly increase the efficiency as well, possibly even past the amount that humans could create themselves.

Methodology

This capstone will be a comparative case study analysis utilizing research and data already collected by other sources. It will combine research from two separate fields, architecture, and botany, to come up with new analysis focused on solving a single problem. Data on plant growth needs, such as light levels, heat indexes, soil needs, and mineral leaching, will provide the necessary understanding of what individual plants need. Next, data on new building materials, such as insulation factoring, solar gain, UV allowance, and the potential for "smart" materials will be collected to inform how greenhouses can be constructed using modern efficiency. Finally, data on how greenhouses are designed based on their environment will be used to ensure the materials can be used. This information will be combined to study how different design options, including shape, size, and planting methods, work in different environments.

Once the design of the greenhouse is considered, this capstone will further analyze how new growing methods can be utilized to increase food production within these facilities. Data will be utilized to discuss how systems such as aquaponics, vertical gardens, and tiered systems can be utilized inside of these facilities to help further efficiency. Information will be gathered that is specific to how the new exterior building materials can also affect these new growing methods, or how some of these materials can be used to support these growing methods as well. This will include using lighter materials to allow more tiers to be built, larger aquaponics tanks, or systems to be hung from ceilings or walls. If we can significantly reduce the weight of these systems, then it will allow for roof construction. The research will also include how to make systems that require power, such as pumps for tiered systems, more efficient, using renewable energy. Also included will be how to combine different methods to increase crop yield over square footage.

By combining research, this paper will aim to be a single source pool of information for increasing greenhouse efficiency. This capstone will also aim to be a stepping stone to furthering urban agriculture. By understanding how to grow more crops in smaller areas, we can understand how to make these systems smaller allowing for more crops to be raised in private gardens, balconies, and other in-home areas. This could lead to a reduction in crop waste by decreasing transportation durations, beauty standards, and people buying more than they need.

Data and discussion

Plant Needs

Because this capstone aims to lead to potential urban agriculture, it will be focusing on crops that can readily be grown in condensed spaces, so it will not include information on plants that need wide swaths of land such as wheat and maize, or tree crops such as oranges, apples or avocados. While there is potential for these crops to be grown in green houses eventually, current limitations allow for smaller individual plants to be more readily grown, such as lettuce, potatoes, and herbs, vined crops such as grapes and tomatoes, or short-stemmed crops such as peppers and beans. While the top 3 crops grown in the United States by Hectare are soybeans, maize, and wheat, which account for nearly 60 percent of total plant calories humans consume, according to the Environmental Literacy Council, only soybeans have the potential to be grown in vertical farms due to their natural needs. Maize and wheat need spread, and their heights do not make them ideal candidates for mass production in urban agriculture, though both could still be grown in smaller amounts if desired. So, by using data from the Food and Agriculture Organization of the United Nations on the crops grown in the United States, which is then filtered by hectares used in their production as surveyed in 2017, a list of top ten viable mass production crops can be assessed.

Table 1 Food and Agriculture Organization US Crops (2017)

Item	Tonnes	Hectares	Tonnes/Hectare	Type
Soybeans (Edamame)	370,960,390	36,228,660	10.4	Legume
Rice, paddy	20,017,350	960,730	20.8	Grain
Beans, dry	10,910,990	814,520	13.4	Legume
Groundnuts, with shell	6,679,211	718,570	9.3	Nut
Sugar beet	5,173,670	450,870	11.5	Root
Peas, dry	76,362	425,130	0.2	Pea
Potatoes	4,615,760	415,010	11.1	Root
Grapes	4,010,800	404,969	9.9	Vine
Tomatoes	1,424,020	126,070	11.3	Vine
Lettuce and chicory	1,306,620	111,900	11.7	Leaf

While there are many other crops grown that make up the agriculture of the United States, these are the most abundant crops with the potential to be grown in the controlled environment of a greenhouse. Information considered during this selection process were nutrient requirements, temperature, sunlight, spacing, and moisture requirements. The growing period was not included because these designs intend to assist in growing crops year-round, meaning they can be spaced out to have consistent production. For ease and uniformity of information, all growing data was gathered from The Old Farmer's Almanac 2019 edition.

Soybeans

- Nutrients: Compost-enriched
- Temperature: greater than 60°F
- Sunlight: Full
- Spacing: 2 to 4 inches apart when planting, 6 inches apart when maturing
- Moisture: steady moisture

Rice

- Nutrients: No additional nutrients required
- Temperature: greater than 70°F
- Sunlight: Full
- Spacing: Thin stocks mean that rice can grow clumped together
- Moisture: 2 to 4 inches of water above soil level

Beans

- Nutrients: No additional nutrients required
- Temperature: greater than 48°F
- Sunlight: Full
- Spacing: (Bush beans) 2 inches apart, (Pole Beans) 3 or 4 seeds at each upward growing position
- Moisture: about 2 inches per week

Groundnuts

- Nutrients: Compost-enriched
- Temperature: greater than 70°F
- Sunlight: Full
- Spacing: 8 inches apart
- Moisture: Well-drained

Sugar Beets

- Nutrients: Less nitrogen-rich.
- Temperature: Between 50°F and 75°F
- Sunlight: Indiscriminate
- Spacing: 1 to 2 inches apart when planting, 3 to 4 inches apart when maturing
- Moisture: about 1 inch per week, but must maintain moisture

Peas

- Nutrients: Compost or Manure-enriched, additional phosphorus and potassium, less nitrogen
- Temperature: Between 45°F and 70°F
- Sunlight: Indiscriminate
- Spacing: 2 inches apart
- Moisture: Sparse

Potatoes

- Nutrients: Compost or Manure-enriched
- Temperature: Indiscriminate
- Sunlight: No direct sunlight on the tubers themselves
- Spacing: 12 to 14 inches apart
- Moisture: 1 to 2 inches per week

Grapes

- Nutrients: Self-Fertilizing
- Temperature: Indiscriminate
- Sunlight: Full
- Spacing: Vines should be planted 6 to 10 feet apart
- Moisture: Steady Moisture

Tomatoes

- Nutrients: Compost or Manure-enriched
- Temperature: Indiscriminate
- Sunlight: Full
- Spacing: 2 feet apart
- Moisture: Well-drained

Lettuce and Chicory

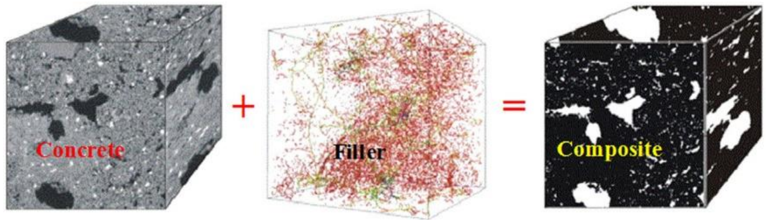
- Nutrients: Compost-enriched
- Temperature: At least 40°F but best between 55°F and 65°F
- Sunlight: Partial
- Spacing: (Leaf style) 4 inches apart, (Cos and Loose-head style) 8 inches apart, (Firm-Head style) 16 inches apart
- Moisture: Moist but not soggy

All of these plants have already been shown capable of being grown in greenhouses of varying styles, with different growing techniques being utilized. Companies such as Bowery in New York City, The Walt Disney Company at all of their major parks, and Sustainable Harvesters in Texas, are already experimenting with growing these foods in smaller spaces and new creative ways.

Building Materials

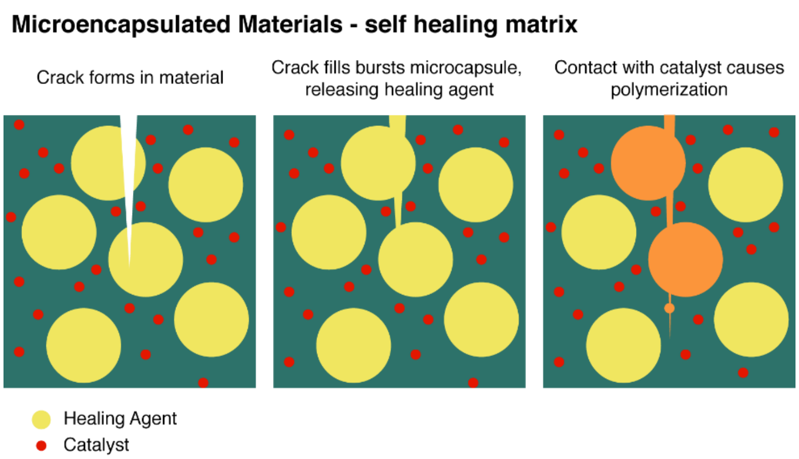
However, while the inner workings of greenhouses and growing methods have been looked at diligently in recent years, there is still room for enhancing the building envelope itself. With the continuous invention of newer and better materials for construction projects, the idea that these ideas can be used in conjunction with greenhouses is a fairly new one. Many of these materials are being created to make large scale developments easier or the fabrication of new technology easier, with only a few people looking into the idea of using them in conjunction with growing food.

Two of the more interesting inventions are "self-healing" or "self-sensing" concrete, which increases endurance and adds the ability to "heal." "Self-sensing concrete (also called self-monitoring concrete, intrinsically smart concrete, and piezoresistive or pressure-sensitive concrete) is fabricated by adding functional fillers (carbon fibers, steel fibers, carbon nanotubes, nickel powder, etc.) into conventional concrete to increase its ability to sense strain, stress, cracking, or damage in itself while maintaining or even improving mechanical properties." (Baoguo Han, et al. 2014) The idea behind this new concrete composition is that when an electrical current is applied the concrete can relay signals back to a computer to measure where the composition has become irregular, meaning damage has occurred. This will be extremely useful in areas that cannot be physically surveyed such as foundations.



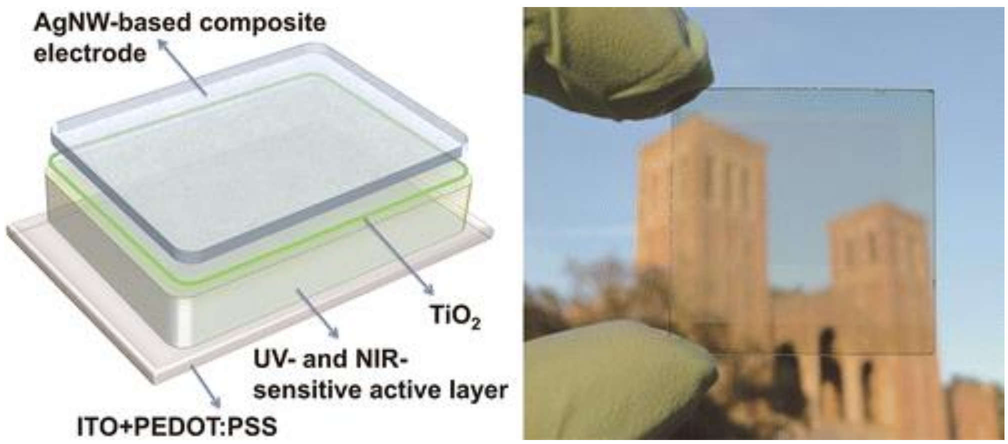
Self-Sensing Concrete at the Macroscopic Level (Baoguo Han, et al. 2014)

On the other hand, "self-healing concrete contains bacteria called *bacillus pasteurii*, along with a form of starch that serves as food for the bacteria (Shubham Maulu, 2012). These bacteria stay dormant in the concrete until a crack forms and air gets in. This change wakes up the bacteria and leads them to eat the starch that has been added to the concrete. As the bacteria eat, grow and reproduce, they excrete calcite, which is a form of calcium carbonate. When the calcite bonds to the concrete it fills the crack and seals it up" (Del Zotto Products, 2019). By utilizing either of these products you can ensure that the concrete you cannot see is still viable. This will allow for the construction of raised beds, tanks, or even shelving to be made from concrete and still maintain peace of mind.

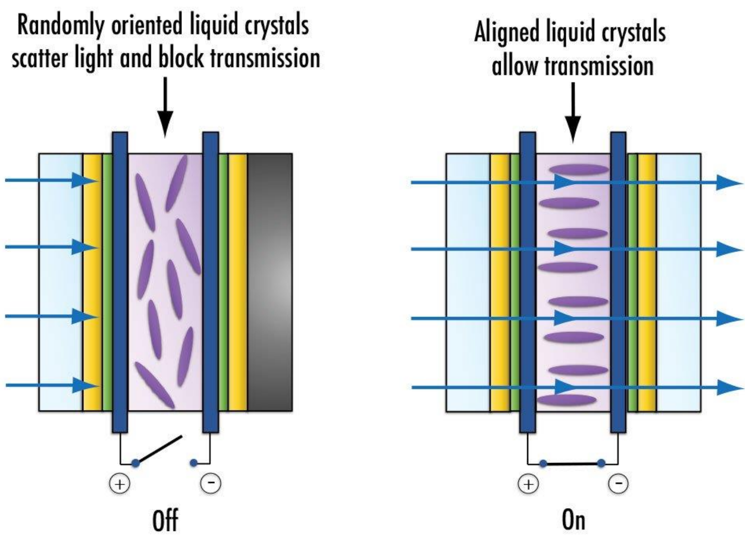


Self-Healing Concrete Diagram (Shubham Maulu, 2012)

Another exciting innovation is the idea of semi-transparent photovoltaic cells. As noted earlier, nearly all major crops require full sunlight, so having siding for the building that blocks the sunlight is not conducive to optimal growth. While sunlight can be supplemented inside of the greenhouse, this should ideally only be necessary during the darker months to alleviate the power draw from this structure. "Most prior work on PV greenhouses focuses on the development of novel semi-transparent photovoltaic (STPV) claddings. The STPV cladding can provide partial shading by encapsulating uniformly distributed crystalline silicon PV cells between glazing materials or using thin-film PV modules. Another promising approach is to use spectrally selective STPV cladding, whereby the sunlight wavelengths that are useful for crop growth serve to generate electricity" (Bambara, 2018). The idea of using PV cells that can absorb different spectrums of light could be extremely beneficial if it allows the main wavelengths that plants need in. By allowing these wavelengths to pass through, it may not matter that the STPV cladding will cast a shadow, which will allow this material to be a great alternative material while the pursuit of completely translucent PV cells occurs.



One product that could work extremely well in conjunction with STPV cladding is electrochromic glass. This glass can change tint levels through the use of electrodes and a small electric charge. "The working electrode designed for monochromatic operation incorporates an Au film patterned with a nanoslit array and conformally coated with a thin layer of PANI. The Au-nanoslit electrode is immersed in an electrolyte solution, along with a Pt counter electrode and a reference electrode. A voltage applied to the working electrode causes electrons (from the metal) and ions (from the electrolyte) to either flow in (reduction) or out (oxidation) of the polymer, thus changing its state of charge and, concurrently, its optical absorption characteristics" (Xu Ting et al. 2016) Because the charge necessary to make these changes is small, it is theoretically possible to utilize this electrochromic glass in conjunction with STPV for power, which can then be used to allow the proper amount of light in for optimal plant growth.



Greenhouse and Growing Design

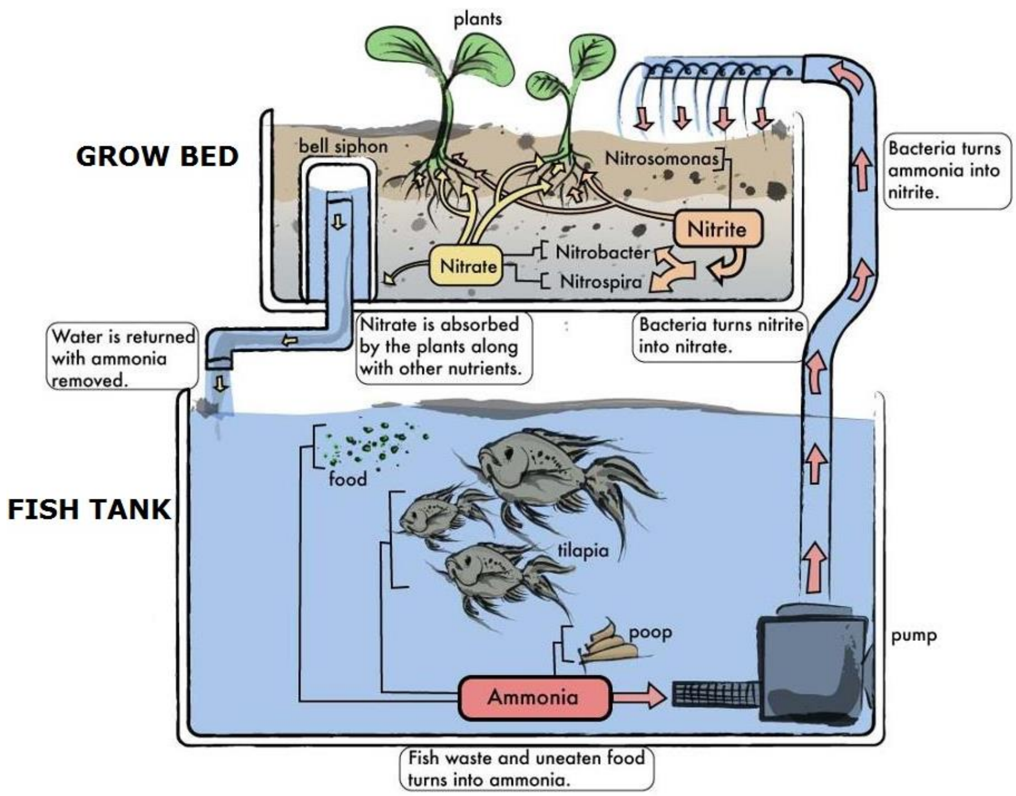
Finally, the design of the greenhouse can be extremely varied, but facility design should be based on the plants that will be grown and the methods used for growth. Depending on the desired crops to be grown, different methods will or will not work, which can completely change the scope of the facility necessary. For instance, leafy greens such as lettuce are able to be grown in aero systems or hydroponic systems, which makes them conducive to being grown in plant factories such as The Bowery Greenhouse in New York City. These plant factories use machines to optimize growth over a series of tiered structures. With minimal human interaction, computes are able to plant seeds in grow pods made out of plant matter, which can retain desired amounts of moisture. They are then revolved through different light systems until they achieve desired growth at which point they can be harvested. Because these factories need to be extremely precise in their measurements, they need to be closed systems, which include exterior light sources, so they are usually built with no windows or exterior penetrations. However, due to current size and mechanical restrictions, these systems are not able to automate many crop varieties, beyond leafy greens.

Sample Vertical Farm – The Bowery in New York City

A different system that can determine design is tower gardens. While these towers can vary greatly in size, from giant towers to towers that will fit into shipping containers, the space needed will be determined by the desired yield. These towers have separate “pods” or “shelves” for individual plants to be grown out of. The spacing that is prevalent in these tower systems offers a wider variety of crops that are able to be grown, including leafy greens, tubers, and smaller fruiting plants such as strawberries. These towers usually employ either a hydroponic misting system or an aero system to provide water to the plants. The general idea is to allow these systems to be soilless and uses a similar plant matter seed pod as the plant factories. The benefit of this style is that, theoretically, it can continuously increase yield without increasing the footprint, by growing vertically. As long as the system is able to support it, the towers can be grown as tall as desired. However, as the towers grow taller, more energy must be expended to bring water to the top and to harvest the plants.

Sample Tower Gardens

The greenhouse-style that has the largest necessary footprint is the aquaponics system, though it only needs to be as big as the desired yield requires. There is work going into combining aquaponic systems with vertical farming at several farms, but this style requires stronger water pumps and filtration systems to ensure the plants only get the necessary nutrients, and the fish have clean water returning to their tanks.



Sample Aquaponics System

Conclusion

In this paper, we have investigated the history of greenhouses and discussed potential future routes for these wondrous buildings. Greenhouses have gone from incredibly simple structures to compute automated facilities that can turn out thousands of plants daily. While these systems are already making incredible strides in food production, more research still needs to be conducted to allow for the mass production of staple crops such as wheat, rice, and maize. For now, these systems are already reducing the need for crops to travel thousands of miles from farm to table, and perhaps someday we will be able to fully replace giant fields with towering gardens. With the constant invention of new growing methods, building design, and construction materials, this future is quickly becoming a reality. As our methods improve, our yields get higher, and our footprint gets smaller.

Current financial and land limitations prevented the ability to perform actual field research during this research, but later studies will allow for example greenhouses to be built.

The aim of these future studies will be to test the construction and growing methods discussed in this paper. By actually constructing these facilities, even on small scale, research will be conducted on what combinations are truly successful and where the cost versus benefit line will be. For the writing of this paper research was limited to information provided by other papers which could not be tested further, and thus had to be taken at the value presented. The hope of this research is to further the ability of greenhouses to grow a variety of food and expand their ability to supply more nutrients from a smaller space then is currently possible. Hopefully, the long-term research will help alleviate the future and looming food crisis. An additional benefit might be the return of farm land to a natural state which might help fight climate change even further.

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