

THE FUTURE OF SUSTAINABLE WHEAT (*Triticum spp.*) IN
CONTROLLED ENVIRONMENT AGRICULTURE

by

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This thesis examines the literature currently published regarding the potential of controlled environment agriculture (CEA) with human-consumed wheat, and the reasoning behind a lack of initiative in growing wheat in a controlled environment/indoor method for commercial purposes. This is done through the use of a brief meta-analysis on literature discussing opinions and insight into the subject along with discussion of CEA technology and potential as it pertains to wheat. By looking at the benefits of controlled environment agriculture in terms of sustainability, efficiency, and profitability involved with other plant species currently cultivated on entrepreneurial scales, the potential for wheat and other staple crops to combat food security and agriculture-based climate change is explored when compared to conventional farming practices.

The Literature Review and Meta-Analysis concluded that of the 33 sources selected from Google Scholar based on a search-term matrix, 17 showed positive reactions to the future of growing wheat sustainably in CEA facilities and 9 showed negative reactions, all up to the authors discretion and from all academic backgrounds.

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Introduction

“The choice is simple: Control everything (indoor farming) or control nothing (outdoor farming).” - Dickson Despommier, page 27 of *The Vertical Farm* (2020)

Agriculture has been a driving force in the development of human society since its beginnings over 11 thousand years ago (Despommier, 2020). Although it caused nutritional deficiencies brought on from a less diverse diet, the development of farming allowed for surplus of food production and a sedentary lifestyle, paving the way for the urbanization we have today (Etkin, 2000). While this is an ancient and seemingly natural practice of humanity, it has been damaging the natural world since its global invention (Despommier, 2020). Soil in the Fertile Crescent, one of the birthplaces of farming, has been depleted of nutrients over millennia of exploitation and drastic environmental changes brought on by the industrial revolution of agriculture in the twentieth century that threaten arability worldwide (Despommier, 2020, Sardare & Admane, 2013). The contemporary overuse of biocides further depleted soil biology and damage its natural systems for replenishing nutrients (Despommier, 2020). Excessive fertilizer runoff continues to threaten our global environmental systems as well (Despommier, 2020). As the world's population continues to grow and urbanize, it is more important than ever for a new industrial agriculture revolution, one that looks at the long-term impacts of its practices and can feed the growing world throughout continued anthropogenic changes in global climate and environmental degradation.

Controlled Environment Agriculture (CEA), which is defined here as indoor farming that controls the factors for plant growth, particularly in hydroponics and to

modern-day standards of efficiency, has a promising potential to be a solution to many of the aforementioned environmental issues (Despommier, 2020). However, types of plants currently grown in these environments on a commercial scale are limited to mostly leafy greens, garnishes, and cannabis (Harris & Kountouris, 2020). While controlled environment cultivation of berries, and even potatoes, exists, this is rare (Al-Kodmany, 2018, Benke & Tomkins, 2017). Many crops being grown and sold commercially in this medium, including staples such as corn, soybean, and wheat, are almost unheard of.

The foods currently grown in vertical farms *do* provide a great deal of necessary nutrients to sustain human life (Mortimer & Gilliam, 2022), but humans do not seem to be willing to give up many other foods in their diets that are not on this list: wheat and wheat-based products included. For instance, many people are now aware of the drastic environmental consequences of our meat consumption but are still unlikely to give up meat for anything that does not taste and feel identical (Kurtz, 2016), a problem companies such as Impossible Burger are working on with synthetic, plant-based meats to satisfy our craving for meat protein (<https://impossiblefoods.com/sustainable-food>). For these plant-based protein sources to be consumed on a large scale, monocultural intensive farming could damage the land and possibly cause more environmental harm than good when switching from traditional animal protein, while CEA, if done well, can hypothetically have no pollution except for the source of energy used to power the energy-intensive system, ideally a renewable source (Despommier, 2020).

Could these possible benefits of CEA, which are still up for debate, be potentially applied to plant species grown monoculturally on a global and climate-

damaging scale such as wheat? Why does this not currently seem to be practiced commercially compared to other edible plant species? These were the questions set out to be answered by this paper.

Choice of Topic

Wheat

There were multiple staple crops considered for research: the main other ones being corn, rice, potatoes, yams, and soybean. All these crops are major parts of the global industrial energy-consuming diet (perhaps apart from yams) and seen in various food products in various amounts and forms. These potential crops are significant sources of nutrition and energy people rely on yet will most likely continue to be constrained in arable land options from climate change and pollution that itself adds to with its current practices (Despommier, 2020). Therefore, innovative practices will be required to continue to improve efficiency and provide for a growing population. CEA is a strong potential candidate to help provide this. However, wheat was determined to be the ideal food for research as opposed to the others for a variety of reasons.

Potatoes and yams were deemed too limiting in culinary and food science capabilities, while rice seemed like a less popular or effective protein to replace meat consumption, in the author's opinion. Corn was a likely choice in initial research but was determined to be potentially confusing due to the capability of an unknown amount of edible corn deemed financially unviable for human consumption and thus turned into ethanol instead. Wheat does not have this problem as much; while many varieties of wheat are grown for livestock feed, this is generally a less fluid economic crossover

than corn's deviation to biofuel (Foley, 2011). Soybean was the second strongest option for investigation but the ability for wheat cultivation practices to contribute to other cereal crops vastly consumed by the world, such as sorghum, made it a stronger contender (Goldschein, 2013).

It is important to determine what is meant by “wheat” in the discussion of future food production, as studies could include species of wheat not typically used. Therefore, anything referring to wheat or the *Triticum* genus was considered for research. The most common type of wheat is bread wheat, or *Triticum aestivum* L. (Duke, 1983). 100 grams of bread wheat should have about 326 to 335 calories and 9.4 to 14 grams of protein (Duke, 1983). The European Space Agency studied the long-term CEA cultivation of *Triticum turgidum* var durum, which has particularly high gluten protein content in the Micro-Ecological Life Support System Alternative Program (Stasiak et al., 2012).

Controlled Environment Agriculture

Controlled environment agriculture can refer to any agricultural practice that uses technological supplements to improve the growing conditions of a crop and even to the extent of complete control of all environmental variables when appropriate. This could be something as small as using a greenhouse to trap warmth in a climate too cold for ideal growing conditions, or even simply modifying the environment through the ancient practices of irrigation, although this alone can barely be considered CEA as opposed to conventional agriculture (Dalrymple, 1973). The Cornell College of Agriculture and Life Sciences defines CEA as “an advanced and intensive form of hydroponically-based agriculture where plants grow within a controlled environment to

optimize horticultural practices”, although this defines the more modern practices of CEA in which more and more of the biological processes involved with agriculture have become separated and independent from their natural counterparts (*About CEA, Controlled Environment Agriculture*, 2022). This definition that focuses on more extreme cases of environmental control are of the most interest to this paper, such as control through hydroponics, humidification, temperature, acidity, light, etc.

Another term referring to these practices in a way of interest to this paper is the “vertical farm”, coined by Dickson Despommier in 1999 and referring to the reasonable expectation that urban indoor agriculture might be stacked in multiple floors to offset the expensive property requirements and save land from being used for wider field farms (*Dickson Despommier*, 2022). Another term commonly used, more often in the eastern half of the world, is the “plant factory”, referenced in Kozai et al.’s *Plant Factory: An Indoor Vertical Farming System for Efficient Quality Food Production* (2015). These are only a few terms being used in this emerging industry; all were considered in this paper and should be considered for future research on CEA and wheat.

Hypothesis

Wheat production using CEA has not become prevalent due to the intense lighting and other energy inputs required for effective growth, the biological mass of the plant that cannot (or is not desired to) be consumed, and the lack of consumer interest and value in what CEA could offer wheat products, such as the promises of fresh and nutritious local greens currently being marketed. However, by redirecting government subsidies that currently benefit other agriculture practices to instead support research

and development and financial growth for new crops in CEA, these techniques could *potentially* limit the carbon footprint and other environmental impacts of production of common wheat crops on a global scale due to localization of food production regardless of climate, as well as be used in places where CEA is more necessary to resolve climate-based food insecurity.

Past and Current Controlled Environment Agriculture

History of CEA

Influencing the atmosphere that the plant grows in via greenhouse technology is one of the rudimentary but essential forms of this paper's definition for CEA and yet still relevant (Dalrymple, 1973). One of the earliest mentions of greenhouse technology known dates to the Roman Empire, between 14-37 BCE, when Emperor Tiberius Caesar had his cucumber garden surrounded by a transparent stone glaze frame that allowed him to grow cucumbers year-round, even transporting the beds and frames indoors when the weather required it (Dalrymple, 1973). CEA was historically quiet from then until the Renaissance in the 15th and 16th centuries, leading to conventional greenhouse designs in the 1800s in Europe and made of materials ranging from cloth, mats, and straw to glass and materials seen in more contemporary design, limited to growing cucumbers, tomatoes, and lettuce (Dalrymple, 1973).

One does not necessarily have to use hydroponics to be considered partly a controlled environment. Soil biology is remarkably complex and integrated with the environment, and hydroponic cultivation provides further control of the environment that soil-based greenhouses and indoor facilities cannot provide. Hydroponics provide the nutrition and hydration directly to the plant using a solution of chemically accessible elements needed for plant growth; this has been referred to as fertigation, or the combination of fertilization and irrigation. The processes of nutrient recycling done by soil leads as deep as regolith and the solid stone below that, and therefore makes sustainable soil-based agriculture within CEA limited in its independence from environmental processes (Brady and Weil, 2004). How can one mimic within a building

the geological processes of the earth's crust grinding into sand, silt, and clay particles, leading to soil production and nutrient cycling (Brady and Weil, 2004)? Because of this, and the level of sophistication and efficiency that hydroponic designs have taken, CEA will be referring to soilless designs for the remainder of this paper unless specified otherwise.

However, hydroponics does not provide the microbiology that soil does to protect plants from disease; therefore, hydroponic cultivation requires much greater control of the sterility and other variables in the greenhouse or indoor facility. Hydroponic agriculture was first used in the 1930s, resulting in mixed opinions on the future of agriculture technology (Despommier, 2020). An article from Scientific American in 1939 called "Plants by Liquid Culture" reviews with enthusiasm at the new practices (Greeves-Carpenter), while a 1940 article from The British Medical Journal berates the idea of large-scale hydroponics due to aesthetic purposes (Gibson). There may be concerns that similar controversies will continue, as CEA methods could be seen as unnatural in a negative connotation, or undesirable for other cultural reasons.

Species Grown in CEA

The majority of crops grown in CEA for commercial purposes are leafy greens and their microgreen counterparts, herbs, flowers, strawberries, and cannabis (Brothill, 2021). A Google search for "vertical farms" provides almost exclusively products and images of leafy greens such as lettuce, arugula, and kale. It is hypothesized here that the logical reasons these species are chosen over others include freshness, value of crop/sensibility to factors, etc.

Organic Hydroponics and CEA

Alongside inorganic nutrient solutions is an increasing field of study on organic nutrient solutions, taking advantage of the efficiency of hydroponics while still relying on biological processes that would typically be seen in soil, or even connect to the nutrient recycling systems of fish as shown in Figure 1. a. Different cultures of microbes in solutions could be used for recycling nutrients, such as described in Kawamura-Aoyama et al. (2014) with a study using lettuce that found this to be an effective way to recover food waste. In 2020 Bergstrand et al. used microbes to help recycle nutrients in a CEA operation. These practices involve the studying of soil biological processes in a soilless medium; organic solutions affect these natural processes and are beyond the scope of this paper, and inorganic solutions will be assumed.

A Sustainable Alternative to CEA: Organic No-Tillage

An alternative promising change in food production to lower environmental impacts is practicing no-tillage to preserve soil biology and therefore resources, as well as energy that would have been used for tilling on an industrial level (Chatrath et al., 2007). This can be seen as the opposite of CEA in the future deviation of current practices, as it relies more so on the natural systems than conventional intensive agriculture as opposed to CEA's strategy of decoupling. Healthy soils can replenish the nutrients and remove the need for excess added fertilizers that can cause tremendous environmental damage when mismanaged, as well as let the soil sequester carbon, though crop rotation/cover cropping is essential to improving the sustainability of this natural nutrition recollection (Laxmi & Mishra, 2007).

In 2021 the Biden Administration implemented economic incentives to encourage no-till practices, specifically in an effort to cut emissions in half by 2030 (Brown, 2021). North Dakota University recommended no-tilling as early as 2014, seeing benefits in the change (Arnason, 2014). No-till was also found to save fuel, despite the need to still plant across the entire field (Creech, 2021). It has been reported that the human race has released 133 billion tons of greenhouse gases through tilling soil in history (Corbley, 2021).

Designs of CEA

As the CEA industry and research has grown, various designs have branched off from the initial concept as more plant species have entered vertical farms, particularly the strategies for fertigation. The primary designs found here to be viable for CEA are Drip Irrigation, Deep Water Culture (DWC), Wicking, Ebb and Flow, Nutrient Film Technique (NFT), and Aeroponics (Bulla, 2022). Examples of these designs can be found in Figure 1. The designs that involve controlling factors such as temperature, humidity, and lighting are less varying or noteworthy.

DWC is a technique that involves a large tank of nutrient solution that hosts a raft for the plants and is shown in Figure 1 d., in which the roots sit in the tank of liquid to absorb nutrients and water; this technique leaves the nutrient solution very still and therefore has challenges in circulating all the nutrients in the tank (Bulla, 2022). The wicking system, which would look similar to 1 c. if the chord below it was of a wick material, takes advantage of capillary action and naturally pulls nutrient solution up into the wick from a reservoir when the plant needs more (Bulla, 2022). Ebb and Flow hydroponics, which can also be represented by 1 c., involves regularly irrigating the

growing medium and roots in between periods of open-air for aeration of the roots (Bulla, 2022). Aeroponics is a particularly impressive and advanced system that suspends the roots of plants in an enclosed area which applies nutrient solution in either a low-pressure spray (Figure 1 e.) or a high-pressure mist (Figure 1 b.) and is of particular interest to space programs such as NASA due to both extremely efficient water usage and the functionality in microgravity (Pandey et al., 2009). The oldest but still a promising strategy for fertigation is the Drip system (Figure 1 f.), which is common for irrigation with soil-based practices in arid climates and relies on correct growing medium properties to retain and release the solution that is dripped (Bulla, 2022). Figure 1 a. is a simple diagram of aquaponics. One

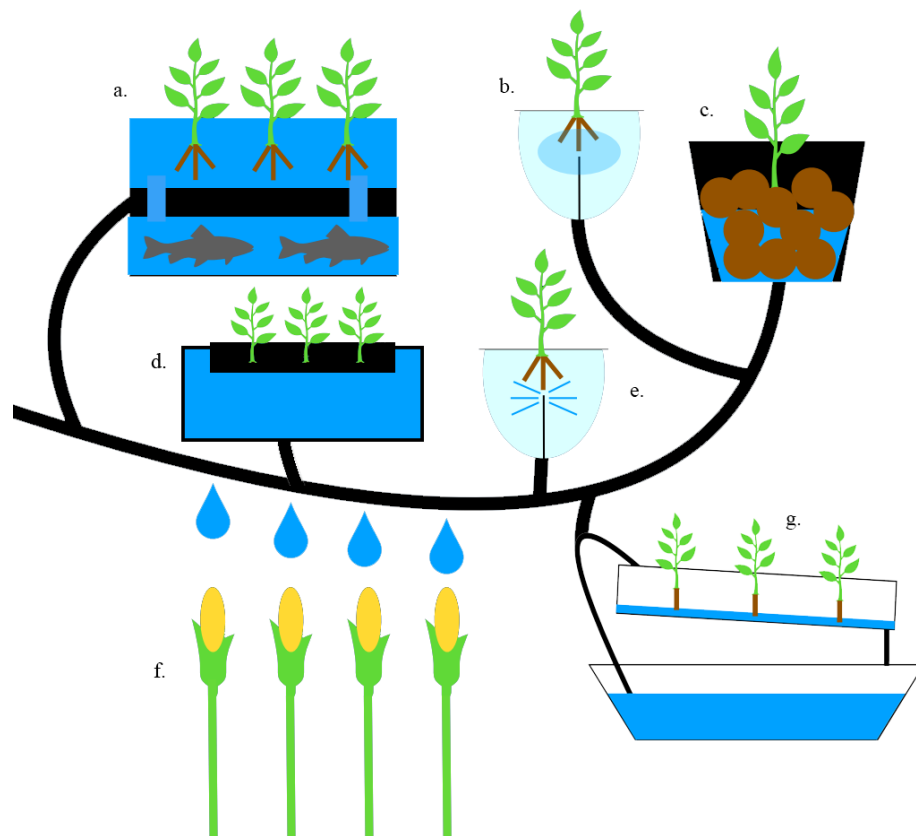


Figure 1: Methods of Fertigation

of the most common methods of CEA fertigation on a commercial scale is the nutrient film technique (NFT), which has seen considerable interest in recent years for its many benefits (Silva et al., 2021). Shown in Figure 1 g., the NFT uses a slope to provide a thin layer of nutrient solution that passes along the bottom of the plant roots, thus providing plentiful aeration and efficient use of nutrients and water (Silva et al., 2021).

Research and Development

For most of the history of CEA, commercial usage has not been feasible for both technological and related economic issues but was instead used as a method of research in what can be referred to as phytotrons, where controlling the environment provides valuable experimental consistency and validity in biological research and could be informative to the research on this paper (Dalrymple, 1973). The development of energy efficiency in lighting has helped for supplementation of sunlight to be more economically worthwhile, allowing for CEA to move from only sunlit greenhouse facilities to completely unexposed environments, some exclusively using artificial light such as the designs sold by Boston's Freight Farms (www.freightfarms.com).

A significant source of research of CEA for sustenance purposes is the collective of government space programs such as NASA, as space provides no environment whatsoever for food production and therefore a fully controlled environment that could hypothetically run indefinitely is needed for long-term missions. The first test of LED lighting for CEA was sponsored by NASA in the 1980s at the University of Wisconsin, and LED technology has been the holy grail of energy-efficient lighting in CEA (Mitchell, 2022). NASA's work on wheat production will be further discussed later in the paper.

Unintentional Experiments Studying Wheat and CEA

As a remarkably consistent way to control factors of growth compared to outdoor experiments, controlled environment agriculture is widely used for studying plants for purposes unrelated to using CEA on a commercial level, such as effectiveness of variations in phenology and their resistance to climate factors; wheat is included in these various studies. In 2014 wheat was grown in CEA for an experiment on different phenotypes and their accumulation of chloride (Genc et al.). Salinity and temperature were varied to see the effect on perfluorinated carboxylic acids (PFCAs) uptake using CEA in 2016 (Zhao et al.). Lastly and most relevant, bread wheat was grown in CEA to test adaptation to heat stress (Telfer et al., 2018). None of these experiments provide significant detail on the CEA strategies and results for growing wheat sustainably and commercially.

Intentional Experiments Studying Wheat and CEA

The number of CEA experiments to test the feasibility of sustainable CEA technology using wheat as the crop of choice is very limited. The majority of the sources that do exist are from the space programs, although these sometimes included and accounted for oxygen life support system supplementing as well (Mitchell, 2022). There is also the mysterious “Republic of South Korea VF” which allegedly grew wheat along with corn and leafy greens on three stories, although there was virtually no available information found on this project (Shamshiri, 2018). A 2012 source claims to yield 5,000 pounds per acre hydroponically over the 600-pound average in the field (Sardare, 2013). Lastly, the consequences of wheat grown in CEA under different light spectrums was studied in 2018 by Monostori et al.

Methods of Research

Methods of researching the questions involved with sustainable wheat production in CEA focused on a thorough and interdisciplinary literature review. While the subject of using CEA for human consumption of wheat seems novel and niche, various aspects of CEA as a whole along with the properties of the biology and economy of bread wheat can provide supplemental information. This could include academic journals reviewing similar subjects, case studies in which wheat via CEA is a control for field studies as opposed to the experiment, or any other reliable source regardless of the intentions of the author's publication.

A meta-analysis and literature review of scholarly work that intentionally reflects on sustainable production of wheat in CEA was also conducted, limited to sources found on Google Scholar for consistency. The literature was searched both through Google Scholar queries and direct findings in these documents that discussed the concept of growing wheat using CEA as defined by this paper and with a focus of sustainability, defined here as focusing on any form of environmental conservation and innovation of resources to provide for present and future generations, or to perform an action mostly independently/from exterior aid, in a closed-loop fashion. Sources were not discriminated by format or academic level, and therefore peer-reviewing was not considered. These sources make up the literature review and are further described on page 16.

It is still unclear which hydroponic system is best suited for wheat production of CEA, as most wheat studies using CEA found in this research did not specify the design of their hydroponics system, and the choices made for such a study might not be

relevant to the best hydroponic setup for growing wheat sustainably for human consumption on a large scale but instead were chosen for simplicity or other unknown factors related to the experiment. Further research must be done to determine the most effective and efficient way to grow wheat in a vertical farming format. NASA has been recorded to use the NFT with wheat production, but reasons were not disclosed; Wheeler claims this as “probably one of the first working examples of a vertical agriculture system” (Wheeler, 2017, p. 19-20).

The larger body of sources was also analyzed as possible benefits to research, both as bodies of information for the discussion and as possible experts in various aspects of CEA, sustainability, and wheat studies. Private CEA operations were also contacted for specific interviews and general information, although little information was provided due to trade secrets and lack of time available to answer said questions.

Literature Review and Meta-Analysis

The segment of research used for meta-analysis was a review of the literature that already exists as a direct reference to the research questions asked in this study. This meta-analysis is therefore on a small portion of the sources cited in this paper, as many other sources were useful but did not specifically and intentionally discuss growing wheat sustainably in CEA. To account for possible variation in terminology, a set of keyword topics were determined and “flushed out” to account for these differences in language, resulting in a set of somewhat redundant search inquiries to be completed on Google Scholar to ensure a complete preliminary examination.

The keywords used can be found in Figure 2 below, with the thicker lines showing the most effective set of search terms. This most focused layer of review was around the literature that was available on Google Scholar and speaks directly and intentionally on the topic of the sustainability of growing wheat in CEA includes all forms of sources found, regardless of the level of detail, perspective, or usefulness of the information. This list, created at the author’s discretion, resulted in 33 sources, all of which are shown as a distribution of number of sources by their publication year in Figure 3. Figure 4 shows a map of the publications by nationality as far back to the original source as possible, although only English sources were included and this should be considered. 18 sources were from the United States, two sources each were found from Australia, India, Kenya, Germany, Great Britain, and Malaysia, and a single source was found in Colombia, Japan, Mexico, Canada, Sri Lanka, France, Hungary, Indonesia, China, Denmark, and Norway.

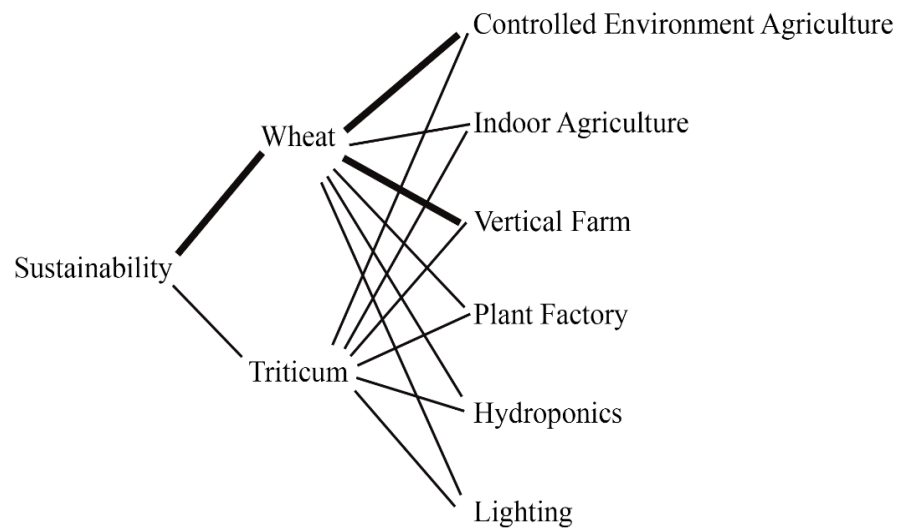


Figure 2: Flowchart of Google Scholar Searches for the Literature Review

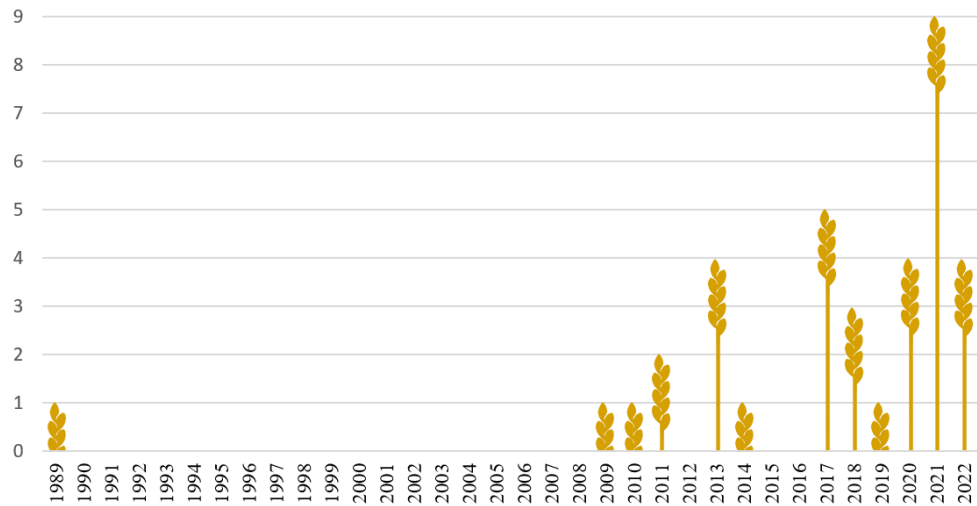


Figure 3: Number of Sources Found in Literature Review by Year Published

Positive Reactions

The 33 main sources used for the literature review varied greatly in perspective, with 17 sources reacting positively to using CEA technology for wheat production. A large portion of positively reacting sources in the Literature Review were based on inferences supporting wheat in CEA for the future, whether this be for climate change or food security or both. Abdullah et al. (2021), Benke & Tomkins (2017), and Besthorn (2013) all refer within their articles on vertical farming to places where wheat production is largely imported, suggesting that CEA could change this. Harris & Kountouris also mention wheat production in present day during an article on vertical farming and directly compare wheat consumption and leafy greens on a global scale (2020). Kibblewhite (2014), Germer et al. (2011), and Lerer & Kamaleson (2020) look at the current and increasing area of land under extreme weather conditions and the benefits that CEA could provide for this issue, while Despommier worries about wheat rust (2011).

Another argument commonly used for wheat and CEA is the yield potential and efficiency of vertical farms growing wheat. Benke & Tomkins reference a 2015 source estimating 3 Empire State Buildings full of wheat CEA to be enough to feed the entirety of the city (2017). Asseng et al. (2020), Chaux et al. (2021), Pandey et al. (2009), and Sardare & Admane (2013) brag about the very high yields that hydroponics have shown with wheat production, while Monostori et al. (2018) and Song et al. (2017) report on the promising efficiencies of LED lighting in wheat CEA.

In 2018 von Kaufmann describes an aeroponics company claiming to be prepared for wheat farming, particularly where regions need it the most and would benefit most from CEA. Hamshiri et al. (2018) is the source that mentions the Republic of South Korea VF, describing it as effective and including wheat. Halliday et al. (2021), Kalantari et al. (2017), and Prawata (2013) all advocate for wheat produced via CEA with theoretical and optimistic mentions of the subject.

Negative Reactions

In the sources reacting negatively to growing wheat in CEA, reasons varied from economics, energy, size of crop, and no explanation. This included 9 sources.

Economic reasons also vary amongst these sources. Al-Kodmany (2018) cites the cheap nature of wheat compared to other crops for its bleak future in CEA. Lubna et al. (2022) instead focus on the high costs of CEA infrastructure and operations, thus making staple crops such as wheat not likely to be seen in vertical farms and concluding the low value of wheat as a crop as the inherent issue.

Both de Anda & Shear (2017) and Kuhn (2019) provide no explanation for why wheat is not feasible in CEA operations, but instead act as if the answer is obvious. However, both suggest the possibility of this changing in the future.

The sources citing energy consumption and efficiency as the main issue made up most of the negative sources. Cox & Tassel claimed in 2010 that a year of CEA for the United States wheat production would be 8 times greater than all electricity generated at the time by U.S. utilities. Iersel only 3 years later (2013) describes the energy needed for lighting alone in terms of dollars, claiming a loaf of bread would cost 23 dollars to produce and not including the energy the building uses for the other environmental

factors. However, it is worth mentioning the improvement in artificial light technology since then. Lerer & Kamaleson also claim as late as 2020 that energy consumption technological improvements are needed. Sablik (2021) quotes that both energy and acreage are indefinite barriers to wheat in CEA, tying back to the size of the plant and the small part of this that is eaten.

The most impressive and comprehensive analysis of wheat production is Sørensen et al.'s Life Cycle Assessment of field and CEA wheat production (2021). Looking at environmental factors involving the two practices extensively, this article also provides one of the biggest let downs of the research process on page 12:

“Based on the results found in this study, it appears that with current yields and photosynthetic conversion efficiencies of wheat, vertical farming is not environmentally preferable to conventional wheat production, even when using electricity generated from the most sustainable sources. VF of wheat may be suitable in locations that are not suited to conventional wheat production (due to a very short growing season, land availability, severe water constraints or environmental pollution), where a low burden source of electricity is available and where food security is of paramount importance, so cost is not so much of a consideration. However, the global market for wheat is likely to provide a more economic and environmentally friendly source of wheat in the foreseeable future.”

This document provides thorough and convincing qualitative data directly on the subject in the present-day economic and technological climate. Please note that Lerer & Kamaleson (2020) and Sørensen et al. (2021) are *preprints*.

Figure 5 shows the different reactions towards the future of sustainable wheat production in CEA by publication year, with some of the 33 sources omitted due to a generally neutral or mixed reaction. The definition of positive (above 0) and negative (below 0) reactions of each source were also up to the author's discretion.

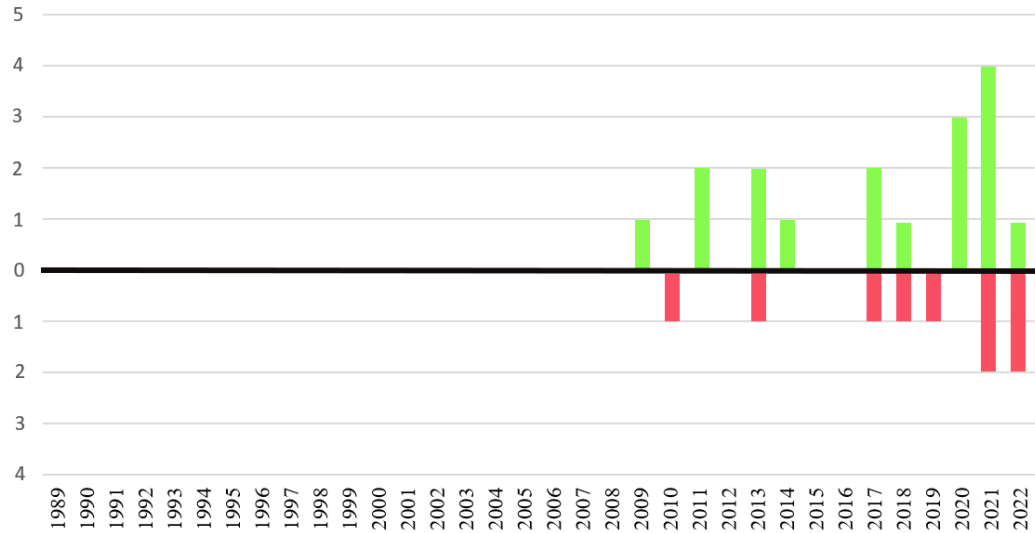


Figure 5: Positive and Negative Reactions in the Literature Review

NASA

Of the sources selected for the Literature Review, 4 documents were relevant in reference to NASA experiments and ideas for CEA in space and on planetary bodies. A study directly from NASA done in 1989 tested the circulation of nutrient solution with wheat with promising results in many tests, although more study for long-term effects was recommended (Mackowiak et al.). Douglas et al. (2021), Mortimer & Gilliam (2022), and Wheeler (2017) discuss the successful yields and sustainability of NASA systems but are difficult to compare to the realities of a financially viable operation.

Discussion

Literature and other written opinions on the subject of the future of wheat in sustainable CEA provided a limited amount of objective information on the practices involved in a potential CEA-fed wheat industry. The complexities involved with Carbon Accounting and Life Cycle Analysis made direct comparison of conventional field agriculture and vertical farming difficult and trivial, as each farm setup and situation results in a different environmental footprint.

Current and Future Wheat Production

Consumption

The United States grew 20 percent of the world's wheat supply from 2009 to 2013, making it the country's third largest crop by acreage (Denicoff et al., 2014). 78 percent of the wheat consumed by the United States was food, the rest being animal feed and seeding. (Denicoff et al., 2014). In 2010, USDA wheat subsidies totaled \$1,731,633,184 across 5,364 recipients, although these subsidies are disproportionately distributed, have encouraged monoculture, and put many small farms out of business (Franck et al., 2013). Despite its dry climate, Saudi Arabia has invested oil money into rural agriculture since the 1970s with subsidies such as a guaranteed profit policy and has become not only capable of wheat independence but became a significant wheat exporter (Bushuk and Rasper. 1994). In the Middle East and North Africa, wheat makes up around 37 percent of consumed calories (Ahmed et al., 2013). In 2005, 20 percent of the world's calories came from wheat (Borlaug, 2008), and around 30 percent of wheat is stockpiled for the next year in case of food insecurity (Aksoy & Beghin, 2004). In

2011, wheat was 18 percent of the world's diet, although it is unclear how much of this is by choice (National Geographic). Wheat exported from the U.S. is mostly brought to port via train as opposed to truck (Marina et al., 2014).

In comparison to this, the most commonly grown plants in CEA make up much less of the world's diet (Harris & Kountouris, 2020); vegetables account for only about 3 percent of the world's diet as of 2011 (National Geographic).

Climate

Modelling software with different potential climate scenarios due to anthropogenic climate change was used in 2013 on the Sistan and Baluchestan province in Iran and the impacts of its wheat production, which found a decrease in wheat growing season, grain yield, and biological yield under every climate scenario simulated (Valizadeh et al., 2014). While a higher concentration of carbon dioxide would have a positive impact on wheat production, especially as it hypothetically improves photosynthesis and water retention, increasing heat will cause rapid evapotranspiration and the shortening of the growing season, creating much more harm than good (Janjua et al., 2010). Therefore, the South African region might have negative consequences to wheat production while in Europe temperature increases might not be enough to offset the benefits of carbon dioxide. Pakistan was still predicted to have an increase in yield despite temperature increases, perhaps from changes in rain patterns (Janjua et al., 2010). Even the beneficial predictions can be misleading in the form of disproportionate negative impacts on hydrology, as was found in a prediction model of West Australia (Ludwig et al., 2009). Northern China wheat production is limited most by lack of water resources (Franck et al., 2013). Widespread irrigation (as opposed to

rainfall dependence) to combat heat stress is becoming less effective and threatening future grain yields, and global wheat yields are predicted to lower thirty percent by 2050 (Zaveri and Lobell, 2019). Associated Press released the following on April 29, 2022:

“NEW DELHI (AP) — An unusually early, record-shattering heat wave in India has reduced wheat yields, raising questions about how the country will balance its domestic needs with ambitions to increase exports and make up for shortfalls due to Russia’s war in Ukraine.”

The reality is that climate and its impacts are too unpredictable for confident answers and therefore will make the future of wheat production unpredictable as well, both in acute disasters and long-term arability, whereas wheat grown in CEA can take advantage of local sunshine, humidity, or temperature when available while still protecting the crops from almost any change in the environment.

Sustainability Potentials of CEA with Wheat and Other Species

Apart from producing wheat, it is important to ensure that CEA can be more environmentally sustainable on a large scale than its alternatives. Generally speaking, and ignoring specific crops, does CEA have the potential to be more sustainable than its alternatives and replace conventional methods of farming? This has been a debate for some time now, as each vertical farm has its own local climate and economy to work with or against, choice of hydroponic practices, nutrient sourcing, energy source of operations, packaging, and distance to the customer’s kitchen.

Figure 6 shows the variables relevant to sustainability when analyzing CEA; it was created by the author and is not necessarily exhaustive.

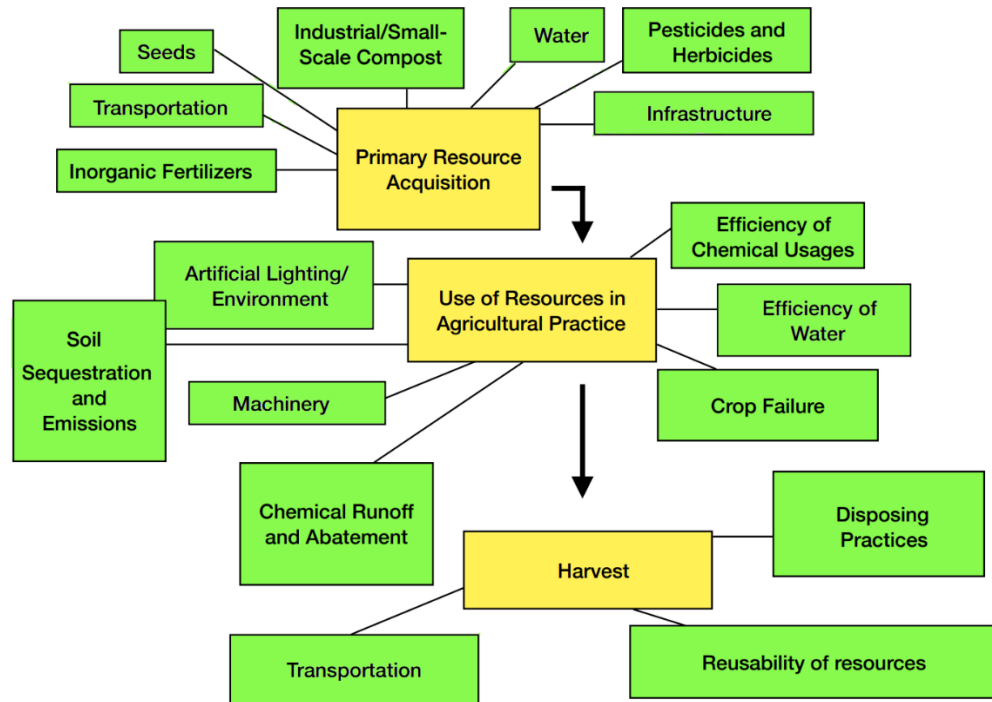


Figure 6: Factors of Sustainability

Water

The efficiency of water usage is one of the biggest proven benefits of using CEA practices and remains a significant argument for companies advocating CEA technology or produce. For decades, CEA has proven to save 70 to 90 percent of the water typically needed (Despommier, 2020). Aeroponics unbelievably uses only 70 percent of the water that other CEA methods use, making it use 4 percent of the water conventional agriculture uses (Despommier, 2020).

Fortunately, wheat is a relatively drought-resistant species, and requires less water input than leafy greens: On average, lettuce provides 1 calorie per gallon of water while bread provides almost 6 calories per gallon of water used, although it should be kept in mind that this is comparing a prepared form of wheat and a raw form of lettuce and more research should be done on quantitative comparisons relevant to the topic

(FatSecret, 2021; FatSecret, 2021; FoodPrint, 2018). Because of the water-saving properties of CEA practices, this efficiency in water could potentially be expanded even further. However, because little water is needed in the first place for traditional agricultural practices, this additional increase in efficiency from CEA might be less significant than using CEA technology for crops that typically require higher inputs of water; it is therefore unclear based on the research findings if the percentages of water saved with CEA techniques would translate proportionally to wheat species on a large scale. While wheat was found to have efficient use of water for its calories, the extent that this benefit compounds with CEA practices is unclear.

Energy and Biomass

As mentioned on page 12, lighting technology has greatly improved the feasibility of wheat in a completely controlled environment. Because of CEA's ability to grow anything anywhere, the thousands of miles that typical food production currently takes to your table are hypothetically no longer required. The energy source of a CEA operation matters greatly in the net carbon footprint and environmental impact that vertical farming provides, and a company that advertises environmentally friendly CEA does not have to disclose if their farms are powered by renewable energy sources or fossil fuels. Energy involved in construction of CEA infrastructure should also be accounted for and considered every year until depreciation, although the environmental costs of infrastructure constructed and used in conventional agriculture practices today makes comparison more reasonable (Despommier, 2020).

It has been made a concern that wheat is too energy-intensive to be viable in CEA, even with cutting edge LED options, whereas this is less the case for leafy greens

(Lubna et al., 2022; Sørensen et al., 2022). More meta-research needs to be done to compare the biomass yield of energy used to grow wheat in a CEA system. When comparing the wheat plant as a whole and the conventional vertical farm crops of choice, the edible and appealing portion of the plant is much smaller with the wheat than leafy greens, as can be seen by the large portion of wheat plants that is stalk and not grain. Even with a good yield, a vast majority of the biomass that was invested in is not going to be eaten and is therefore a major disincentive for CEA companies to attempt wheat.

Artificial lighting costs, even at very efficient rates, can account for half of the energy expenses (Asseng et al., 2020). It is essential that CEA be powered by clean energy to compete with the other agricultural strategies in terms of sustainability, although conventional agriculture has many drastic impacts as it is (Despommier, 2020). The value of wheat as a crop with so little appealing biomass also brings into question its place in the vertical farming industry, although massive agricultural subsidies currently in practice for conventional agriculture must be considered when comparing the economics of the two practices.

Nutrients

While fertilizer runoff of intensive agriculture today is worse than what CEA fertilizer produces when performed properly (Despommier, 2020), there is still a need for sourcing these inorganic nutrients found in a hydroponics solution, and this aspect of hydroponics seemed somewhat overlooked in most academic papers on sustainable CEA found for this research. Sardare and Admane provided a detailed analysis in 2013 of converting soil into inorganic hydroponic solution, but this requires disturbing the

soil for extraction and losing its biological carbon-capturing abilities and carbon reserves it has gained over time, as healthy soil can have remarkable carbon-stocking capabilities (Blanco-Canqui, 2013). Despommier (2020) provides the most promising idea of a closed-loop system for nutrients on page 197, in which no inputs are extracted from nor outputs tossed into the natural world: “With the advent of plasma arc gasification (PAG) devices, any solid material can be reduced to its elements in a matter of seconds. PAG uses an electrical current to create a high-energy plasma, the fourth state of matter.” PAG can even generate six times more energy than it uses through the heat created (Despommier, 2020).

Plant Health

Without the proper use of hygiene when operating a CEA facility, diseases that plants cannot defend themselves from without soil organisms can wreak havoc on hydroponic crops; with proper measures taken, however, these field diseases will never reach the growing setup and pesticides will be obsolete (Despommier, 2020). Wheat grown in the field is at risk of diseases such as rust *Puccinia graminis* amongst other types of rust fungi (Kolmer et al., 2009). Nematodes are another environmental hazard for wheat (Smiley & Nicol, 2009). With properly performed and advanced CEA practices involving sterility, these would no longer be an issue (Despommier, 2020). Gibson (2018) sees the benefits wheat provides for long-term storage and dryness being the driving force of their consumption, and says that growing produce that is sold and valued fresh such as leafy greens is more worthwhile in CEA and peri-urban setups. On top of this, he mentions the need for ultraviolet light in a CEA operation to keep the

wheat disease-resistant, although this should not be an issue in a properly-run (and therefore sterile) CEA operation.

Subsidies

One of the bigger arguments against the feasibility of wheat being commercially grown in CEA is that it is not economically worthwhile to grow such a low-value crop. However, it could easily be argued that current agricultural practices are not financially viable either, as they are heavily subsidized. A common subsidy provided to farmers by the government is insurance for the case of natural disaster or general crop failure, and this would not be an issue with CEA (Špička et al., 2009). While the search for sources on Google Scholar discussing the topic of CEA and sustainable wheat production found more sources having optimism for its future, some of the most comprehensive and conclusive studies still point to the negatives under current economics and technology.

Conclusion

By setting out to determine the future of sustainable wheat production in controlled environment agriculture, more questions were asked than answered, and a final verdict remains unavailable. By looking at the current practices of CEA, such as the economic and environmental benefits, and searching for literature that has asked the same questions of the future of agriculture for staple crops such as grains, the current market for bread wheat would not easily permit a commercial CEA operation, even in the developed world, without subsidies such as those other agricultural practices benefit from. As climate continues to change and the world's population grows in size and in appetite, unorthodox ideas such as CEA must be seriously considered as a new revolution of global food production and distribution, leaving soil-based planting of food crops to landscaping and recreational gardening.

While it is easy to see the charismatic rural family model and their farming practices as ancient and unchanging ways in which humans interact with the environment, the invention of farming is relatively contemporary in human history and in many ways has been a failed experiment (Despommier, 2020). The destructive consequences of conventional agriculture cannot be ignored, especially with the increase in population and quality of life predicted to continue. Current farming and ranching practices take up land acreage the size of South America, and 2050 is predicted to need an additional Brazil-sized amount of land to provide for the world population, which is more than there is arable land (Despommier, 2020). By decoupling agricultural dependence with nature on a large scale and with a diverse diet of crops, food security can be further assured while still accessing natural resources such as

sunlight, humidity, and temperature when optimal while protecting crops from the elements in controlled environment structures.

Future Research

While there is a small amount of academic literature arguing a perspective on whether wheat is worth cultivating via CEA for sustainability reasons, plenty of individuals of various disciplines and levels of education and experience could provide valuable insight into the topic. It was unclear how CEA and subsidies work from the research conducted, and this should be further investigated. In early research, multiple large-scale producers of vegetables using CEA were contacted and asked about the sourcing of their hydroponic solution nutrients, as a part of the research focus on sustainability, but no answers were given, either due to lack of time available from them or trade secret concerns. Further research and authorization of interviewing human subjects is required to provide a larger pool of direct opinions, perhaps through an email survey using a mix of multiple choice and short answer responses that are not too time consuming.

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