Mitigating Imported Vegetable Dependency in the United Arab Emirates through Indoor Farms: The Financial and Environmental Impact

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Accessibility
Mitigating Imported Vegetable Dependency in the United Arab Emirates through Indoor Farms: The Financial and Environmental Impact

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A Thesis in the Field of Sustainability
for the Degree of Master of Liberal Arts in Extension Studies

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Abstract

The world’s population is projected to increase by 30% in 2050, to 9.5 billion persons. This will require 60% more food to be produced than is done today, all in the face of inevitable increases in the price of water, energy, and agricultural resources. Such a stark picture mandates finding solutions outside conventional farming methods to ensure the survival of future generations (Al-Kodmany, 2018). Throughout the world, billions of dollars in subsidies for the traditional agriculture industry have been made by governments in order to protect consumers from food scarcity and rising prices (Goodman, 2015). Such a practice impedes innovation. New methods such as indoor farming could provide promising alternatives in support of increased global demand.

Indoor farming is the practice of growing produce in controlled hygienic environments powered by light-emitting diodes (LEDs). This practice marks a recent shift to applying techniques such as hydroponics, aquaponics, or aeroponics. The indoor farm concept is a novel way of growing produce that reduces water consumption and the use of pesticides and herbicides, while generating high quantities of nutritious, quality fresh food year-round. The technology is largely independent of weather conditions, thus providing a solution to an arid region’s future food security predicament.

As a desert terrain country, the United Arab Emirates (UAE) struggles to produce its own food. This research, a first of its kind in the Middle East, addressed the critical question of whether the UAE government should shift its current emphasis on importing food (85% of its fruits and vegetable) to building its own food sources through
systematized indoor farming. I hypothesized that indoor tomato farming would be more cost-effective by requiring lower operational yearly expenditures while generating higher profits than does the current process of importing tomatoes. My research targeted the environmental impacts of both conventional open-field farming and importing tomatoes to the UAE, versus supplying these from domestic indoor farms. A second and related hypothesis was that indoor farming would have a lower environmental impacts.

To test these hypotheses, I quantified the environmental impacts of both the import model and that of in-house indoor farming by pursuing a comprehensive literature review in addition to working with a farm in the UAE to gather necessary data. I then built economic and life-cycle assessment models to measure the economic and environmental impacts, respectively, of both approaches. Last, I applied a sensitivity analysis to the environmental model by looking at an alternative energy source, photovoltaics (PV), for indoor farms, and an alternative growing scenario, heated greenhouses, for imported tomatoes. While results revealed both environmental disadvantages and advantages of the indoor farming of tomatoes over importing them, nevertheless, the current structure of indoor farms and their projected profitability based on a variety of loan schemes and periods showed that over the long term (15 years), they are a more profitable business venture than the import model.

This study will likely be of value to UAE government policymakers, to entrepreneurs thinking of starting an indoor farm and to the UAE’s sustainability and food security plans, and to environmentalists broadly. While this study is aimed at the UAE, it certainly applies to other countries—especially those in the Gulf Cooperation Council with desert regions that are heavily dependent on food imports.
Acknowledgments

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Chapter I

Introduction

Although food security has been a critical issue in the past century, with recent environmental pressure from skyrocketing populations, lack of water reliability, and climate change, the world is at risk of limited food availability. Moreover, by 2050 the world’s population is projected to require 60% more food than it does today (Fleischmann, 2013). The United Arab Emirates (UAE), a small oil-rich country with a desert landscape, faces a hard time in producing its own produce—vegetables and fruits—due to the harshness of its weather and non-arable terrain. Further, the political unrest of its surrounding nations deters the UAE from dependence on other countries for its own food stability, making enhanced food diversity a vital objective of the UAE (Ministry of Climate Change and Environment [MoCCAE], 2017). Currently, up to 85% of the UAE’s food is imported (Gokulan, 2017). As the country’s population is increasing rapidly, from 1.9 million in 1990 to 9.5 million in 2017 (GMI Blogger, 2018), the demand for food is likely to increase in the coming decades. While 70% of the world’s future population will be living in urban areas, the UAE has already surpassed this number, as 84% of the population already lives in urban areas (e.g. Dubai) (Fanack, 2009). The increased urban population will inflate the demand for food imports and cause declines in yearly food production due to decreased popularity in the farming profession (Despommier, 2011). Given the UAE’s extreme climate, can such a country produce its own vegetables?
With the recent revolution in urban farming in Asia, Europe, and the United States, ranging from traditional small outdoor community gardens to complex indoor vertical farms (VF) where produce is grown in vertically stacked layers, one might ask why the UAE hasn’t followed suit—especially as certain types of indoor farming can be more environmentally friendly than importing food from the global world market. Although several studies have furnished conclusions regarding both the environmental (Muñoz et al., 2008; Romeo,Vea, & Thomsen, 2018; Graamans, Baeza, Dobbelsteen, Tsafaras, & Stanghellini, 2018 ) and economic impact (Eaves & Eaves, 2018; Banerjee & Adenaeuer, 2014) of indoor/greenhouse farming, none of these studies have been done in the context of the Middle East–Gulf region. If research could show that the concept of indoor farming can be adopted in a profitable and environmentally friendly way, the UAE government might begin to solve its food security and dependency problem.

Research Significance and Objectives

This study examined the economic and environmental effects of substituting imported Italian tomatoes, specifically Cuore Di Bue (sometimes referred to as Ox Heart tomato) and Plum tomatoes, with similar tomatoes produced through indoor farming in the UAE. Such a study has never been performed in the region. Because the race for food sovereignty is a central issue in the Middle East, this case study research aimed to examine if indoor farming could help achieve this aim.

Therefore, this research intended to address four critical objectives:

1. To evaluate the environmental performance of partially replacing the UAE’s imported tomatoes with those from locally produced indoor farms.
2. To study the economic performance of alternative indoor farming technology to ensure its validity and viability against imported tomatoes.

3. To understand whether alternative tomato farming technology can be more economical and sustainable within the extremes of a desert terrain such as that of the UAE.

4. To guide government policies toward informed decisions and initiatives regarding the support of indoor farming in the UAE.

Background

Food security is one of the fundamental issues of the 21st century. In the coming decades, urban populations will exponentially increase. The United Nations predicts that the world population will increase by 30% in 2050, becoming 9.5 billion, of which 70% will reside in cities. Consequently, food demand is projected to increase by 70% (due to a larger, more urban and richer population) to fulfill the needs of the additional 2 billion people in 2050 (The United Nations, 2017; Manning, 2015). Not surprisingly, agronomists, ecologists, and geologists are predicting a future decrease in farmable land, resulting in food demand exceeding supply, possibly leading to global famine (Al-Kodmany, 2018).

The price of food has been increasing over the past decades, and the trend is not dwindling, especially with increases in the price of water, energy, and agricultural resources (Al-Kodmany, 2018). According to the United Nations’ Food and Agriculture Organization (FAO), there existed 0.23 hectares of farmable land per person in 2002 as opposed to 0.42 hectares in 1961. This was due to increases in population, urbanization
and climate change (Al-Kodmany, 2018), stressing the need for new technologies and food production methods.

Farming and Food Supply in the United Arab Emirates

The UAE, located in the eastern corner of the Arabian Peninsula, contains two cities that have been growing exponentially over the past decade, with projections that Dubai—one of the seven Emirates—will double its population by 2027, reaching around five million people as opposed to 130,000 who lived there in 1975 (Zaatari, 2016). By 2040 only 2% of the current agricultural land might be available for use (Banerjee & Adenaeuer, 2014).

The Middle East’s farming and agriculture sectors are inherently weak since most conventional farming is out of the question, given the desert terrain and an average yearly rainfall of 800-110 milliliters (Sherif, Almulla, Shetty, & Chowdhury, 2014). Additionally, the UAE’s agriculture industry itself is limited and heavily concentrated on dates (Aquastat, 2008) (Figure 1); these data remain similar today.

Abu Dhabi, the most agriculturally productive emirate, has roughly 74,986 hectares of farmable land. Al Ain, is a city in the Eastern Region of the Emirate of Abu Dhabi, contributes the majority of the farmable land (56.7%). Fruit trees are found on 33% of the farmable land, of which the majority are palm trees—a common tree in Gulf climate conditions. Vegetables grown by conventional farming, along with those from greenhouses, contributed to only 2.6% of total farmed land. Moreover, the total farmable land for vegetables did not change significantly between 2012 and 2016, i.e., 1,700 as opposed to 2,000 hectares, respectively (Statistics Center, 2017; Figure 2).
Because agriculture accounts for only 3% of the GDP of the UAE, the country must import the majority of its fruits and vegetables from India, the United States, Australia, and Canada—its three biggest suppliers (Figure 3; Nexus, 2018). The country currently imports roughly 25,000 tonnes of fruits and vegetables every day (Shaaban,
Consequently, over the past decade, a surge in reliance on imported food has resulted in the country’s increased dependency on global food production and its supply system—a dependency that can cause instabilities whenever major economic or political disruptions arise. Several factors put the UAE’s future required supply of food at risk: the global food supply experiencing large-scale changes (e.g., pandemics and decreases in arable land), climate change, reductions in conventional farms yields, contraction of land availability, extreme weather events, and decreases in fertilizer supply (Romeo, Vea, & Thomsen, 2018). Based on such trends, the UAE needs to find new ways to supply its own produce.

Environmental Impact of Importing Produce in the UAE

Importing 85% of its produce underscores the fact that the UAE promotes conventional agriculture across the world and therefore is responsible for environmental impacts beyond its borders, e.g., climate change and impacts upon the world’s arable
land. Conventional agriculture currently uses 70% of the world's freshwater, in many places makes it hazardous to drink due to the effects of herbicides, pesticides and other contaminants (The World Bank, 2020; Aktar, Sengupta, & Chowdhury, 2009).

Furthermore, farming in the US consumes up to 20% of the fuel supply of gasoline and diesel, thereby contributing significantly to greenhouse gas emissions. Since the UAE is dependent on various produce imports from the US, it indirectly contributes to these emissions (Vermeulen et al., 2012; Ivanova et al., 2016). Farming per se places a huge burden on the land. Moreover, agrochemicals have contributed in destroying the natural cycle of nutrient renewal that maintain intact ecosystems (Despommier, 2009). The UAE’s continuous reliance on imported produce perpetuates these negative environmental impacts.

To counteract negative agricultural effects on the environment and health, new techniques such as indoor farming, which reduces the amount of land utilized due to the stacking and boasts independence from pesticides, have been publicized and promoted across the world.

Indoor Farming

Four main types of technologies are currently used in indoor farming: hydroponics, aquaponics, aeroponics, and dryponics. Hydroponics, the oldest of the three, derives its name from the Greek words hydro and ponos which translate to “water works” (Munoz & Joseph, 2010). Hydroponic systems cultivate plants without soil and are solely dependent on nutrients and water (Figure 4), reducing the risk of soil-related cultivation problems (i.e., the insects, fungus, and bacteria that grow in soil); (Al-
Aquaponics is a technology that integrates aquaculture with hydroponics using a bio-integrated system (Diver, 2006). The waste product of fish, ammonia (NH₃), is broken down by bacteria into nitrates (NO₃), which are absorbed by the plants returning clean water for the fish (Figure 5), a system that saves a substantial amount of water through this biological filtration process. The combination of fish and plants develops a polyculture that increases diversity and yields multiple products (Diver, 2006).

Aeroponics, developed by NASA, is a more advanced system of hydroponics using mists instead of water trays. The main difference between aeroponics and hydroponics is that the former does not have a growing medium, while the latter uses water as its medium (Al-Kodmany, 2018). The system uses 95% less water than
conventional systems (Cooper, 2013). Although the technology is gaining a lot of traction in the industry, aeroponics is currently an anomaly.

Dryponics, a fairly new technology developed by Japanese polymer physicist, Dr. Yuichi Mori., is defined as “plants grown on a thin film made of hydrogel [that] absorb water and nutrients through nano-sized pores.” He adds, “Viruses and bacteria are blocked by the film, allowing a very safe product without the use of chemicals. Because of the film barrier and low water usage, the crops grow slightly more slowly than normal, which accelerates the synthesis of sugar and amino acid leading to high sweetness and nutrition” (Hughes, 2018, p. 9) (Figure 6).

Environmental Impacts of Indoor Farming

In the United States, traditional farming contributes to over 20% of all gasoline and diesel fuel consumption. Moreover, food travels on average 1,500 miles from farm to table and 90% of the food in major US cities is sourced from outside the city. Research by Carnegie Mellon University concluded that food transportation contributed to 0.4
tonnes of CO$_2$e emissions per household per year (Al-Kodmany, 2018). Regarding VF, there is conflicting research when it comes to the environmental impact. Some studies suggest these systems have a lower environmental impact compared to that of conventional farming (Kulak, Graves, & Chatterton, 2013; Sanyé-Mengual, Oliver-Solà, Montero, & Rieradevall, 2015), while others point in the opposite direction (Goldstein, Hauschild, Fernández, & Birkved, 2016). In fact, according to one view, even though urban farms reduce metropolitan density level they do more harm to the environment than good (Blaustein, 2011).

On balance, however, despite some weaknesses the strengths and opportunities of indoor farming indicate that desert regions, taiga regions, and megaregions are potentially the biggest markets for indoor farming, with the UAE being a perfect candidate by satisfying two of these regional conditions, i.e., that of desert and megaregion (Banerjee
Vertical Farming

Another variation in improving food production in urban settings is vertical farming. The idea of vertical farming is not modern, having existed in 600 BC in the hanging gardens of Babylon. The most popular theory is that gardens were built by King Nebuchadnezzar II for his wife since she was homesick and missed the gardens of her hometown (Cartwright, 2018). People referred to the gardens as hanging since they were built high above the ground on multi-level stone terraces. The hanging vegetation on the terraces created a pleasant aesthetic as well allowing for easier irrigation (Cartwright, 2018). In 1915, Gilbert Ellis Bailey, professor of Geology at the University of Southern California, published *Vertical Farming* in which he discusses the history of conventional farming and then introduces the concept of hydroponic technology, arguing the advantages and economic benefits of this approach. William Frederick Gericke later in early 1929 pioneered modern hydroponics at the University of California, Berkeley, a technique by which plants held in their place without any soil have water mixed with nutrients circulated over them (Despommier, 2009). In 1980, Åke Olsson, a Swedish ecological farmer, promoted the idea of using hydroponics to produce vegetables in cities (Al-Kodmany, 2018). Recently, at the beginning of this century, Dickson Despommier, an American ecologist and Professor of Public Health at Columbia University, started the urban farming revolution. Despommier urged his readers not to fend off VF just because it requires the cutting-edges of technology, agriculture, and agronomy, arguing that all of this is achievable (Despommier, 2011).
As for today, the urban agriculture (UA) movement has already started with cities such as Brooklyn, Barcelona, and Lyon deploying such farms in their densely populated urban neighborhoods. UA can be deployed in settings as varied as those of small commercial farms, community-supported agricultural plots and gardens, rooftop gardens or greenhouses, and indoor agricultural settings (Romeo, Vea, & Thomsen, 2018). Within this movement, vertical farming has become increasingly prominent.

Vertical farming has several forms. The first iteration was seen on rooftops of both old and new residential and commercial buildings, restaurants, and grocery stores. A second type of vertical farming was implemented within constructed warehouses, buildings, or indoor farms where several growing beds were stacked vertically. Recently, there has been a surge in businesses building high tech indoor farms from scratch, powered by LED lights that leverage artificial intelligence (used to analyze the wealth of data from sensors and lights in order to reach optimal yields). These farms are highly sterile and operate in controlled environments that remove all forms of bacteria and dust. This form of innovation decreases risk of plant disease (Frommer, 2014). This approach is common and is being developed in many countries across Europe, North America, and Asia.

The Future of Vertical Farming

Proponents and visionaries also would like to see vertical farming techniques applied in high-rise (multi-story) buildings. As an example of this, a concept that won the Green Dot Award, is that of the Urban Skyfarm located in downtown Seoul, South Korea. Urban Skyfarm bio-mimics a tree with four major components, root, trunk, branch, and
leaf, in which each has its own characteristic for multiple farming conditions (Figure 7).

Figure 7. Example of Urban Skyfarm in Seoul, South Korea.

Urban Skyfarm is a net-zero facility that operates from photovoltaic energy and wind turbines. It also supports environmental quality by filtering water and air; producing greens (through hydroponics, vertical gardens, and farming decks); relying on renewable energy; and by reducing heat accumulation, stormwater runoff, and carbon dioxide (Aprilli, 2014). Although there have been several proposals by other cities to adopt this visionary idea, as of today none of them have been acted upon.

Advantages of Indoor Farming in the UAE

Among the many advantages of indoor farms that can mitigate the UAE’s agricultural footprint are increased crop production through year-round farming,
optimized crop-yield methods, protection from weather-related incidents (through certain indoor controlled environments), enhanced water conservation and recycling through hydroponic technology, lowered transportation costs by situating farms in urban locales, novel ecosystem creation, greenhouse gas reduction, and the pesticide-free/non-GMO character of distinctively organic products of Indoor farms (Dastoor, n.d). Despite these positive attributes, few studies have explored the economic and environmental feasibility of such farms.

The effects of flooding, hurricanes, storms, and droughts can be seen in the decrease of arable land which has affected many countries’ economies. For example, the United States has lost around 110 billion dollars due to drought, a loss scientists expect to continue. Although these climate effects negatively impact the UAE’s food imports and price of produce, governments continue their support of traditional farming (Al-Kodmany, 2018). Furthermore, houses emit, on average, 0.4 tons of CO₂ in order to bring their food home, a sizable amount (Blaustein, 2011).

Conventional farming causes erosion, soil contamination, and water waste. Moreover, the use of animal waste as fertilizer currently being adopted by 50% of the world's farms has a result of luring flies bearing diseases that can affect human health when affected products are consumed (Al-Kodmany, 2018). Growing crops indoors reduces the excessive use of pesticides and herbicides that lead to hazardous runoff and excessive nutrient release. This eutrophication accelerates the proliferation of algae, and when the plant dies, microbes consume algae and suck oxygen from the water, resulting in dead sea animals (Al-Kodmany, 2018). Indoor farms, on the other hand, use 90% less water through precision irrigation.
The agriculture industry currently uses more than two-thirds of the earth’s fresh water, a volume that will increase in the future due to higher produce demands and climate change. Furthermore, over the past century the Brazilian Amazon region has suffered deforestation, with 1,812,992 km$^2$ (700,000 miles$^2$) having been cleared for farmland. If the UAE decreases its dependency on conventional farming imports and adopts the indoor farming concept, conversely, its sharply reduced land requirements can decrease agricultural impact on the world’s ecosystems, restore biodiversity, and mitigate the negative influences of climate change.

Indoor farming, if developed in the UAE, would lead to more competitive produce prices, especially desirable given the ever-rising global price of produce, while creating a more stable food source. The strategic location of indoor farms in urban areas can reduce the UAE’s transportation costs of its produce, which now represents 60% of the produce cost (Al-Kodmany, 2018). VF can produce 20 times more than can a conventional farm having the same area by planting vertically in combination with the advanced technologies and artificial intelligence currently used to optimize light intensity, light color, space temperature, CO2 content, water, and air humidity level (Al-Kodmany, 2018). Finally, VF provides an important opportunity to support the UAE’s economy and lower its unemployment. Indoor farming is still in the initial phase of expansion. Research continues to pour into this industry, improving its technology and lowering costs. The current situation regarding VF resembles that of mobile phones in the 1990s: extremely expensive and awkward in size. Fast forward 20 years, and mobile phones are ubiquitous, under 100 USD, and smaller than one's palm.
Indoor Farming in the UAE

The first indoor (vertical) farm in the UAE, Badia Farms, established in December 2017, uses hydroponics technology coupled with agri-tech methods that optimize growing conditions (Khaleej Times, 2018). The farm sits on 799 m² (8,600 ft²) of land in Dubai’s industrial neighborhood and produces a range of micro-greens and baby leaf herbs such as arugula, kale, mint, and mustard (Ettinginer, 2018). Since the launch of Badia Farms, indoor farming technology has been a hot topic in the UAE. Recently, the Emirates partnered with the Silicon Valley-startup Crop One to build the world’s largest VF. The facility is expected to grow to roughly 12077 m² (130,000 ft²) and to produce three tonnes of produce a day (Irving, 2018). Furthermore, the UAE government recently, signed a deal with Shalimar Biotech Industries to build 12 vertical farms in the city. The ministry will allocate 7600 m² (81,805 ft²) of its land for the farms (The National, 2018). Last, Kuwait’s Wafra International Investment has committed 100 million dollars to Pure Harvest, a greenhouse company in Abu Dhabi that produces tomatoes (Nair, 2020).

Recently, there has been a push to understand and research innovations to promote indoor farms. The Abu Dhabi Investment Office in early 2020 announced that it would commit 100 million US dollars (USD) in investment in four farms (AeroFarms, Madar Farms, RNZ, and Responsive Drip Irrigation) in order to develop new research and development (R&D) in indoor farming in Abu Dhabi. Aero Farms will conduct research in genetic phenotyping and organoleptic, Responsive Drip Irrigation will research a new innovative irrigation system to transform water usage in the UAE, Madar farms will develop new methods to scale commercialization of tomato and microgreens.
farms in order to provide a consistent and predictable local food supply, and RNZ will develop its own R&D center (Abu Dhabi Executive Council, 2020).

To the best of the author’s knowledge, few academic studies have looked into the impact of VF in the UAE (Graamans et al., 2018; Eaves & Eaves, 2018). Specifically, very few studies outside the UAE, or similar regions in general, have studied the environmental and economic impact of indoor farming versus conventional farming (Banerjee & Adenaeuer, 2014), and the generalizations of these are hard to apply to the UAE due to the vast economic, climate, and political differences. Yet with any rapid expansion of VF in the UAE, it becomes imperative to take a step back and look holistically at the economic viability and environmental impact of such farms and compare results to current standards.

Life-cycle Assessment

As environmental awareness increases across the globe, many businesses, governments, and researchers are adopting methods to measure the environmental performance of goods and services. Life-cycle assessment (LCA) is the prominent method to assess environmental performance. LCA is a cradle-to-grave assessment method that reviews all processes, from raw material extraction to waste-handling (Curan, 2006). The idea of LCA started in the late 1960s and early 1970s in the United States. Coca Cola is often cited as one of the first companies to adopt LCA. They were considering self-manufacturing and wanted to analyze the economic and environmental impact of using metals with a plastic container, a revolutionary idea at the time (Hunt & Franklin, 1996).
Application of Life-cycle Assessment

Several studies have considered the environmental impact of greenhouse farming in relation to various types of produce (lettuce and strawberries); (Romeo, Vea, & Thomsen, 2018; Martin & Molin, 2019; Romero-Gámez, Audsley, & Suárez-Re, 2014; Khoshnevisan, Rafiee, & Mousazadeh, 2013; Goldstein, Hauschild, Fernández, & Birkved, 2016). Other studies have specifically assessed the impact of growing greenhouse or indoor-produced tomatoes. Hendricks and Van Acker (2012) assessed the environmental impact of eight greenhouses in Ontario, Canada, discovered that heating contributes to the bulk of the environmental impact. In examining various heating alternatives, they found that choosing a “best” heating scheme is quite challenging. Two other studies reached similar conclusions. A study of a Finnish greenhouse concluded the method to be quite energy intensive, consequently having the most significant emissions (Keskitalo, 2009). The other study looking at the environmental impact of a greenhouse versus a glasshouse for rose crops in both cold and warm European cities reached similar conclusions in that the main impact came from the energy consumed by a greenhouse structure and by the use of fertilizers (Torrellas et al., 2012). Other studies did similar comparisons on country levels (Boulard et al., 2011; Bojacá, Wyckhuys, & Schrevens & Schrevens, 2014; Almeida et al., 2014). A study by He et al. (2016) took a somewhat different approach by assessing the environmental impact of both organic and conventional greenhouse tomato production.

Only two studies have compared the impact of greenhouse-produced tomatoes versus conventional open-field produced tomatoes. A preliminary study in Spain
concluded that greenhouse tomatoes had a lower environmental impact in the depletion of non-renewable resources, acidification, eutrophication, energy consumption, and water consumption; however, this growing method had a higher impact on global warming (Muñoz et al., 2008). The second concluded that greenhouse tomato production in Iran had a greater negative environmental impact than conventionally grown tomatoes, resulting from the energy needed for the heating system of greenhouses (Zarei, Kazemi, & Marzban, 2019).

These particular studies are only peripheral to this research since they do not consider the UAE, a region of very different climate conditions than those of Spain and Iran. Additionally, these studies compared greenhouses as opposed to indoor farms, a wholly different model that does not exploit sunlight since it is fully enclosed, utilizing LED lighting (as the main source of energy needed for photosynthesis).

Research Question, Hypotheses, and Specific Aims

My primary research question was as follows: Is indoor farming of tomatoes an environmentally and economically viable approach in the UAE?

In order to address this question, I tested the following hypotheses:

- Indoor farming has a less negative environmental impact than does the process of importing tomatoes
- Because indoor tomato farming is more cost effective than importing the same food, it is more profitable than the current process in the UAE
Specific Aims

To fulfill my research objectives/questions and test my hypotheses, the tasks I needed to complete were to:

1) Conduct a systematic review of indoor farming techniques such as hydroponics, aeroponics and aquaponics, and review previous economic and environmental results relevant to analyzing models for the UAE.

2) Understand the economics behind conventional open-field tomato farming by looking at transportation, labor, water, fertilizer, and pesticide costs among others.

3) Understand the business model for indoor farming by looking at labor and energy needs, specifically heating and cooling costs, mainly through interviews and literature review for adaptation to the UAE case.

4) Define and quantify the environmental impact of both the food-import model and indoor farms themselves.

5) Apply sensitivity analysis to the environmental model to understand the impact of a variety of estimated variables on the overall results.

6) Recommend how the government can incentivize indoor farming and to support and set them up for success.
Chapter II

Methods

This study examined the economic and environmental impact of replacing imported tomatoes with those grown locally in indoor farms. In order to develop the empirical material needed for these assessments, interviews with relevant parties in academia, consulting, farming, and business enterprise were conducted. From these interviews, data were gathered to conduct the life cycle assessment (LCA) and build an economic model in Excel. The following sections outline this process.

Case Study Comparison of Tomatoes

This study assessed the projected future production of locally hydroponically grown Plum and Cuore Di Bue tomatoes in Abu Dhabi, United Arab Emirates (UAE) by Madar Farms (Madar Farms, 2020). Madar Farms is currently building the largest fully indoor tomato farm in the UAE. The total land area of the project is 71,000 m$^2$ (76,4237 ft$^2$); for this study, however, I examined phase one of this project, comprising 9,000 m$^2$ (9,688 ft$^2$); of the land area, of which 4,500 m$^2$ (48,438 ft$^2$) will be utilized for growing. The facility is expected to produce roughly 310,000 kgs/yr of Cuore Di Bue and 73,000 kgs/yr of Plum tomatoes once operational (Wagner, 2019). The indoor facility (Figure 8) will be built by Certhon Greenhouse Solutions, a Dutch company formed in 1896, specializing in greenhouses. It is important to highlight that the facility being built is not a traditional greenhouse, but rather an indoor facility since it will be fully enclosed and
depended on light-emitting diode (LED) lights.

Figure 8. Typical section views of a vine crop highwire greenhouse on which the Madar Farms structure is based.

The indoor facility will utilize established commercial scale greenhouse growing technology, adopted to the indoor environment to cultivate tomatoes. For lighting, the farm will employ over 5,500 LED horticultural fixtures, of which 4,200 will be mounted on the ceiling, and 1,200 inter lighting fixtures will be placed between the tomato plants (Figure 9). Moreover, an innovative and highly efficient climate control system will be used in the indoor facility to keep temperatures and humidity consistent to avoid the volatility that can affect the tomatoes. Rockwool will be used as the growing medium.

Both Plum and Cuore Di Bue tomatoes were also used for the imported case study comparison. These were assumed to be produced in northern Italy and transported by (air) freight to the UAE, then stored in a cold storage facility before being packaged and distributed across the UAE.
Environmental Impacts of Imported and Locally grown indoor Tomatoes

To test the first hypothesis, that indoor farming would have less of a negative environmental impact than imported tomatoes, I conducted a life cycle assessment (LCA) of each model production system. This was followed by a sensitivity analysis to assess how various inputs affected the overall impacts of the reviewed system.

Life Cycle Assessment (LCA)

Life cycle assessment is an environmental impact assessment tool employed to assess the environmental impact of products or services in all stages of their life cycle. LCA is a fitting tool to use in agriculture and has been implemented numerous times as discussed in the previous chapter. Life cycle analysis has four steps which were structured by ISO14040/44 (Curan,2006):
1. Goal Definition and Scoping: One of the most important stages that outlines the purpose of the LCA. It defines boundaries and environmental effects for the LCA.

2. Inventory Analysis: Looks at all environmental inputs and outputs associated with a study (e.g., raw materials, air emissions, wastewater discharges)

3. Impact Assessment: Creates conclusions to understand decisions affecting a study/business.

4. Interpretations: Evaluates results of the inventory analysis, determination of data sensitivity, and results presentation (Curan, 2006); (Figure 10).

---

![Life Cycle Assessment Framework](image)

Figure 10. Life cycle stages (Curan, 2006).
The goal of the LCA was to estimate the environmental impact of locally grown indoor tomatoes, Plums and Cuore Di Bue to be specific, against the same tomatoes grown in Italy and imported to Dubai. The functional unit of the LCA study was defined as one kilogram of fresh commercial tomatoes produced. The study was limited to a cradle-to-gate perspective, meaning from raw material up until the plants are available to consumers at the retailer. It included considerations of material input, infrastructure, energy inputs, transportation, and waste. The packaging of the tomatoes along with consumer waste handling were excluded from the study since the farm is still not operational and management have not decided on the type of packaging to use. See Figure 11 for a depiction of the system boundaries and all included processes.

Figure 11. System boundary and functional unit of the study.
Indoor-Grown Tomatoes

The assessment for indoor-grown tomato included all material and energy inputs required for the system. This includes the infrastructure employed by Madar Farms for cultivation, which includes the indoor facility (steel structure, gutters, sandwich panels, crop wire etc.) along with the LED lighting systems. Raw materials such as rockwool, nutrients (nitrogen, phosphate, and potassium), water, and seeds were also considered. Lastly, energy inputs (from heating/cooling, ventilation and lighting), waste from the indoor facility and transportation were taken into consideration (Table 1). LCI data from, Ecoinvent v 3.4 was used unless otherwise specified; for a list of LCI inventory data employed, refer to the Appendix, Table 11.

Table 1. Material and energy inputs for the annual production of indoor-grown indoor tomatoes.

<table>
<thead>
<tr>
<th>Main Category</th>
<th>Process/Flow</th>
<th>Amount</th>
<th>Unit</th>
<th>Lifetime(Years)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Infrastructure</td>
<td>Indoor Facility</td>
<td>4,500</td>
<td>m²</td>
<td>25</td>
</tr>
<tr>
<td></td>
<td>LED</td>
<td>50</td>
<td>Kg</td>
<td>7</td>
</tr>
<tr>
<td>Raw Materials</td>
<td>Seeds</td>
<td>12,500</td>
<td>Number of seeds</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>Nitrogen (N)</td>
<td>2,039</td>
<td>Kg</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>Phosphate (P)</td>
<td>450</td>
<td>Kg</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>Potassium (K)</td>
<td>3,295</td>
<td>Kg</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>Rockwool</td>
<td>18,000</td>
<td>Kg</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>Water</td>
<td>3,386,470</td>
<td>Liters</td>
<td>-</td>
</tr>
<tr>
<td>Energy Inputs</td>
<td>lighting</td>
<td>1,368,020</td>
<td>KWh</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>heating and cooling</td>
<td>6,530,580</td>
<td>KWh</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>ventilation</td>
<td>131,400</td>
<td>KWh</td>
<td>-</td>
</tr>
<tr>
<td>Transportation</td>
<td>Aircraft transport of seedlings</td>
<td>5,158</td>
<td>Tonne-km</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>Land transport of tomatoes</td>
<td>26,810</td>
<td>Tonne-km</td>
<td>-</td>
</tr>
<tr>
<td>Outputs</td>
<td>Waste</td>
<td>58,561</td>
<td>Kg</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>Tomatoes</td>
<td>383,000</td>
<td>Kg</td>
<td>-</td>
</tr>
</tbody>
</table>
Assumptions. The lifetime of the indoor facility (i.e., the closed greenhouse) was retrieved from the Ecoinvent dataset, and assumed to be 25 years. The LED fixture lifetime was retrieved from Madar Farms and their conversations with their provider (Wagner, 2019). The weight of the LED lights was not provided by Madar farms; consequently, the number of lights was extracted from the providers websites and multiplied by the total number of LED units and the weight of an LED light, retrieved online and from a study performed by the Swedish Environmental Research Institute (Martin, & Molin, 2019). The farm is located in Kizad, Abu Dhabi. Thus, it was assumed that there would be weekly produce deliveries to both Abu Dhabi and Dubai. An average distance from the farm location to central Dubai and Abu Dhabi was taken as the input for LCA. Nutrient data for tomato production was provided by estimates from Madar Farms as parts per million (PPM) over the life cycle of the tomato cultivation (Table 2). These numbers were translated to kilograms per liter and multiplied by the water usage in liters. Waste from the indoor farms was difficult to estimate as the farm is not in operation. Therefore, waste was assumed to be similar to a study of greenhouse tomato production (Dias et al., 2017). Lastly, carbon dioxide was not used in this assessment as the farm has not yet started operations.

Table 2. Nutrient use over the tomato cultivation cycle.

<table>
<thead>
<tr>
<th>Nutrients/elements</th>
<th>Receipe for tomato growth (PPM)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>week 0-6</td>
</tr>
<tr>
<td>Nitrogen (N)</td>
<td>224</td>
</tr>
<tr>
<td>Phosphorus (P)</td>
<td>47</td>
</tr>
<tr>
<td>Potassium (K)</td>
<td>281</td>
</tr>
</tbody>
</table>
Imported Tomatoes

The assessment for imported tomato included all material and energy inputs required for the system. This included the conventional tomato farming cultivation process (including all the inputs needed to produce the tomatoes), energy inputs (storage facility), maritime transportation from Italy, as well as land transport to producers in the UAE (Table 3). For a list of the inventories used refer to Table 12 in the Appendix.

Table 3. Material and energy inputs for the annual production of 383,000 kg of imported tomatoes.

<table>
<thead>
<tr>
<th>Main Category</th>
<th>Process/Flow</th>
<th>Amount</th>
<th>Unit</th>
<th>Lifetime(Years)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tomatoes</td>
<td>Conventionally produced tomatoes</td>
<td>383,000</td>
<td>Tons</td>
<td>-</td>
</tr>
<tr>
<td>Energy Inputs</td>
<td>Cooling</td>
<td>26,280</td>
<td>Kwh</td>
<td>-</td>
</tr>
<tr>
<td>Transportation</td>
<td>Maritime transport of tomatoes</td>
<td>3,504,730</td>
<td>Tons x KM</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>Land transport of tomatoes</td>
<td>37534</td>
<td>Tons x KM</td>
<td>-</td>
</tr>
<tr>
<td>Outputs</td>
<td>Waste</td>
<td>58,561</td>
<td>Kg</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>Tomatoes</td>
<td>383,000</td>
<td>Kg</td>
<td>-</td>
</tr>
</tbody>
</table>

Assumptions. Conventional tomato production was assumed to be done in open fields with a similar output as indoor tomatoes, i.e., an annual total production of 383,000 kg to allow for functional equivalence. Cooling for the warehouse in Abu Dhabi was assumed to consume 26,280 kWh of electricity per year based on discussion with Madar Farms (Wagner, 2019). Transportation was split into maritime (or air) transport which included the distance from northern Italy to Dubai, and land transport. The distance traveled was assumed to be greater than for locally grown indoor (sometimes referred to as locally grown) tomatoes (roughly 1.5 times) to take into account the distance traveled.
from the farm in Italy to the port as well as the distance from the port in Dubai to the
storage facility (this number also included transportation to retail).

Impact Categories and Impact Assessment Method

Impact categories were defined as ramifications from the input and output stream of
commercial tomato farming on present humans, future generations, plants, animals, and
recourse depletion used to measure the environmental impacts of a specific study
(Curran, 2006). The impact assessment method used in this study was ReCIPe Midpoint
(H), a choice based on expert opinion expressed within the literature reviewed, as most
studies adopt the midpoint method which makes it easier to compare results. This study
assessed the following eight impact categories of the 18 available in the Recipe
methodology:

1. Land use (LU) - m² crop eq,
2. Fossil resource scarcity (FRS) - kg oil eq,
3. Human non-carcinogenic toxicity (HNCT) - kg 1,4-DCB,
4. Human carcinogenic toxicity (HCT) - kg 1,4-DCB,
5. Global warming (GW) - kg CO₂ eq,
6. Terrestrial acidification (TA) - kg SO₂ eq,
7. Marine eutrophication (ME) - kg N eq, and
8. Water consumption (WC) - m³.

The categories chosen were based on discussions with LCA researchers in conjunction
with related research studies that identified leading factors in conventional and indoor
tomato cultivation (Romeo, Vea, & Thomsen, 2018; Martin & Molin, 2019; He et al.,
Sensitivity Analysis

The processes that lead to the largest impacts for the impact categories assessed were also reviewed further through sensitivity analyses in order to assess the effects of different inputs on the overall environmental impact of both locally grown and imported tomatoes. As such, an alternative energy source, photovoltaics (PV), was modeled for indoor farms to substitute the conventional electricity used in the UAE. Moreover, an alternative growing scenario, heated greenhouses, was used for imported tomatoes. Lastly, an alternative transportation scenario, air freight, was utilized for imported tomatoes (which was mentioned as the most common mean of transportation by the head of operation in Madar farms). Different combinations of the three scenarios were compared to identify their effect on the eight impact categories. All datasets employed in the sensitivity analyses are included in Table 13 of the Appendix.

Economic Impacts of Imported and Locally Grown Indoor Tomatoes

A comparative financial appraisal of indoor farming versus the conventional importing of tomatoes over different loan periods was conducted. This compared the cost of locally produced indoor-grown Cuore Di Bue and Plum tomatoes with the cost of importing both types of tomatoes by air freight from Northern Italy to the UAE.

Madar Farms agreed to share information about its facility, including the technology used for. Financial and operational farming data was collected from Madar Farms records, reports published by governmental entities, and papers in academic
journals.

Capital Expenditure Assumptions

Most estimates of capital expenditure costs for local indoor tomatoes were retrieved from discussions with the Head of Operation and head of Sales and Logistics at Madar Farm (Wagner 2019; Soliman 2019). Variables for local indoor tomato capital expenditures were grouped under sections: construction (e.g. foundation, building erection, and sewer drainage), climate control system (air conditioner chiller and dehumidification system), procurement of hard-wall and installation (e.g. sandwich panels, hot and cold water tanks, flooring), regulatory fees (e.g. water and electrical connection fee, design approvals, and civil defenses fee), LED lighting, growing structure materials, heating and cooling materials, irrigation materials, and electric hardware. For conventionally imported tomatoes, costs were derived from interviews with suppliers in Dubai along with discussions with the Head of Sales and Logistics at Madar Farms, and from online research. Variables for imported tomato capital expenditure were grouped under the storage facility section.

Operational Expenditure Assumptions

Information for operational expenditures was retrieved using the same approach as that for capital expenditures. Variables for local indoor tomato operational expenditures were defined and grouped under the following sections: electricity, employee wages (farm supervisor, sales, admin assistant, executive level, and marketeers), labor wages (growers and harvesters), water, nutrients, seeds, packaging,
transportation (air freight from Italy to the UAE and land transport from the port to storage facilities and distribution centers), consumables, and carbon dioxide production.

For imported tomatoes, variables were also defined and grouped under sections: import for Cuore Di Bue, import for Plum tomatoes, labor, employees, electricity, packaging, and transportation. Maintenance cost was not taken into consideration since the farm was not yet operational.

Revenue Assumptions

Most revenue assumptions, specifically the sale price of Cuore Di Bue and Plum tomatoes, were retrieved from the Head of Sales and Logistics at Madar Farms (Wagner 2019; Soliman 2019). Three different mediums are available for selling tomatoes in the UAE: wholesale markets, distributors/traders (basically selling to stores), and restaurants. Each of those uses a different market price, which vary by the time of year. I was able to retrieve the bottom and upper threshold prices from the Head of Sales and Logistics in Madar. Furthermore, Madar Farms will be selling its tomatoes in the wholesale market.

For the imported tomato model, I assumed that 50% of the tomatoes will be sold to restaurants and the remaining 50% to distributors; pricing estimates were taken from Head of Sales and Logistics (Soliman, 2019). Next, I took the average of the upper and lower threshold prices when building the model for both the imported and locally grown models. An exception was for Cuore Di Bue locally grown tomatoes, for which I used the upper threshold, as the Madar Farms Head of Sales and Logistics said that would be the price aimed for during contract negotiations.
Chapter III

Results

In determining the potential environmental impact and economic performance of indoor-grown Cuore Di Bue and Plum tomatoes as compared to an import model, this section explores the LCA results, three different sensitivity analyses, and an economic model to review the cash flow and projected profitability based on a specified interest amortized over a variety of loan schemes and periods.

An LCA of 1 kg of tomatoes was performed, and the results for the eight different impact categories were compared for imported tomatoes versus locally grown indoor tomatoes. Figure 12 presents the overall contribution of 1 kg of tomatoes for the two scenarios, showing the units of each impact on top of each plot. Indoor-grown tomatoes had higher values in many of the impact categories, including FRS, HNCT, HCT, GW, TA, and ME; however, the indoor-grown tomatoes illustrated a lower impact in LU and WC (Figure 12).

Since the locally grown indoor tomatoes model produced a higher impact across the majority of the impact categories (except for LU and TA), the locally grown indoor tomatoes model was used as the base, i.e., scaled at 100%, and compared against imported tomatoes (Figure 13).
The two impact contributions, FRS and GW, had the most significant differences when comparing locally grown indoor tomatoes against imported tomatoes (Figure 13), roughly 97% greater for both. ME was 105% greater for imported tomatoes versus the locally grown ones. It can be concluded that GW had the highest percentage difference (Figure 13) and the largest absolute difference between the two growing methods assessed (Figure 12).
Life-cycle Impact of Locally Grown Indoor Tomatoes

In analyzing the life-cycle impact of indoor tomatoes, it may be seen that electricity contributed significantly to all impact categories except for ME and WC (Table 4). Furthermore, electricity contributed nearly 96% of the GW impact category (11.4 of the total 11.9 kg CO$_2$ equivalent emissions). For further details on results for imported tomatoes refer to Table 14 in the Appendix.
Table 4. Life-cycle assessment of producing 1 kg of locally grown indoor tomatoes.

<table>
<thead>
<tr>
<th></th>
<th>LU (m2a crop eq)</th>
<th>FRS (kg oil eq)</th>
<th>HNCT (kg 1,4-DCB)</th>
<th>HCT (kg CO₂ eq)</th>
<th>GW (kg CO₂ eq)</th>
<th>TA (kg SO₂ eq)</th>
<th>ME (kg N eq)</th>
<th>WC (m3)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Green house</td>
<td>2.50E-05</td>
<td>3.32E-03</td>
<td>7.23E-03</td>
<td>9.54E-04</td>
<td>3.66E-03</td>
<td>1.85E-05</td>
<td>1.36E-07</td>
<td>3.72E-05</td>
</tr>
<tr>
<td>Nitrogen (N)</td>
<td>3.31E-04</td>
<td>4.40E-02</td>
<td>4.85E-02</td>
<td>1.09E-03</td>
<td>5.83E-02</td>
<td>2.12E-04</td>
<td>1.49E-06</td>
<td>5.04E-04</td>
</tr>
<tr>
<td>Phosphote (P)</td>
<td>1.37E-04</td>
<td>1.82E-02</td>
<td>5.54E-03</td>
<td>1.29E-04</td>
<td>2.35E-03</td>
<td>1.97E-05</td>
<td>1.02E-07</td>
<td>6.96E-05</td>
</tr>
<tr>
<td>Potassium (K)</td>
<td>1.77E-04</td>
<td>2.36E-02</td>
<td>2.23E-02</td>
<td>9.68E-04</td>
<td>2.55E-02</td>
<td>9.02E-05</td>
<td>8.20E-07</td>
<td>1.73E-04</td>
</tr>
<tr>
<td>Rockwool</td>
<td>4.87E-04</td>
<td>6.47E-02</td>
<td>4.64E-02</td>
<td>2.15E-03</td>
<td>6.83E-02</td>
<td>4.15E-04</td>
<td>1.86E-06</td>
<td>4.39E-04</td>
</tr>
<tr>
<td>Seeds</td>
<td>2.88E-04</td>
<td>3.83E-02</td>
<td>6.59E-05</td>
<td>4.90E-06</td>
<td>1.49E-03</td>
<td>4.63E-07</td>
<td>2.76E-09</td>
<td>2.28E-05</td>
</tr>
<tr>
<td>LED lights</td>
<td>4.19E-03</td>
<td>3.17E-02</td>
<td>1.23E-01</td>
<td>2.07E-03</td>
<td>4.07E-02</td>
<td>1.78E-04</td>
<td>1.91E-06</td>
<td>3.54E-04</td>
</tr>
<tr>
<td>Electricity</td>
<td>4.19E-03</td>
<td>4.75E+00</td>
<td>1.01E+00</td>
<td>5.95E-02</td>
<td>1.14E+01</td>
<td>6.71E-03</td>
<td>2.50E-05</td>
<td>2.14E-02</td>
</tr>
<tr>
<td>Aircraft transport of seedlings</td>
<td>1.02E-05</td>
<td>1.36E-03</td>
<td>7.92E-04</td>
<td>8.93E-05</td>
<td>1.47E-02</td>
<td>4.22E-05</td>
<td>4.08E-08</td>
<td>2.48E-05</td>
</tr>
<tr>
<td>Land Transport of tomatoes</td>
<td>7.43E-04</td>
<td>9.87E-02</td>
<td>2.15E-02</td>
<td>1.28E-03</td>
<td>4.36E-02</td>
<td>1.09E-04</td>
<td>4.32E-07</td>
<td>1.20E-04</td>
</tr>
<tr>
<td>Water</td>
<td>4.62E-04</td>
<td>6.14E-02</td>
<td>3.48E-02</td>
<td>4.60E-03</td>
<td>5.55E-02</td>
<td>2.13E-04</td>
<td>2.28E-06</td>
<td>2.26E-02</td>
</tr>
<tr>
<td>Waste</td>
<td>4.34E-04</td>
<td>5.77E-02</td>
<td>1.41E+00</td>
<td>2.38E-03</td>
<td>1.16E-01</td>
<td>1.83E-05</td>
<td>7.95E-05</td>
<td>5.05E-05</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>7.53E-03</strong></td>
<td><strong>1.00E+00</strong></td>
<td><strong>2.73E+00</strong></td>
<td><strong>7.53E-02</strong></td>
<td><strong>1.19E+01</strong></td>
<td><strong>8.03E-03</strong></td>
<td><strong>1.14E-04</strong></td>
<td><strong>4.58E-02</strong></td>
</tr>
</tbody>
</table>

In order to further analyze the effects of the input processes on the life cycle impacts, the percent contribution of each input for each specific impact assessment was examined (Figure 14). Waste had the highest impact, over 50%, for both HNCT and ME. Water use in the indoor farming operations contributed to roughly 49% of the WC. Lastly, electricity contributed over 50% in all of the impact categories, except HNC, ME, and WC (Figure 14).

Factors Influencing Electricity in the Locally Grown Indoor Tomatoes Model

Upon further investigation, it was found that three processes contributed to the bulk of the impact from electricity consumed in the indoor tomato facility: dehumidification and cooling, lighting and ventilation. Additionally, dehumidification and cooling contribute to the majority of the electricity impact for GW (81%).
Figure 14. Percent contribution for different processes for producing 1 kg of locally grown indoor tomatoes for the reviewed environmental impact categories.

(Figure 15). This is mainly due to farm design, which is optimized to keep the growing environment as close to optimal at all times for maximum yields.

Sensitivity Analysis

In this section three sensitivity analyses are presented. These include assessing sensitivity to the data and assumptions made on the origin and production methods for the imported tomatoes. The first assessment compared locally grown indoor tomato powered
Figure 15. Electricity mix contribution of producing 1 kg of locally grown indoor tomatoes.

with photovoltaics (PV) versus conventionally grown imported tomatoes. Here the source of the electricity was changed from the UAE’s (conventional) electricity mix to that of photovoltaics. The second analysis reviewed the sensitivity of the origin of the imported tomatoes. Instead of assuming that these were imported from a crop of conventionally produced tomatoes on farmland, they were assumed to be grown in a heated greenhouse in Italy. The third analysis assumed the imported tomatoes are air freighted instead of sea freighted. Thereafter, the results of the different sensitivity scenarios were compared.
Alternative Electricity Scenario for Locally Grown Indoor Tomatoes Analysis.

In order to test potential changes in the electricity supply, and given the location, the conventional electricity supply was replaced by photovoltaic (PV) electricity. The life-cycle impact produced by the two electricity alternatives was compared, in which conventional electricity was used as the base (Figure 16). A negative percentage change implies an improvement in the PV case and vice versa for a positive percentage. As illustrated, GW and FRS may be significantly improved by 83% and 90% (Figure 16), respectively, due to the independence of the electricity grid. WC, TA, ME, LU, HNCT, HCT, however, show a negative impact due to the effects of the life cycle involved in the building of photovoltaic units.

The life-cycle assessment comparison of locally grown indoor tomatoes powered by PV versus that powered by conventional electricity portrays a significant decrease in FRS and GW; however, both impact categories still have a higher impact against imported tomatoes, 0.48 vs. 0.19 kg oil equivalent and 2.07 vs. 0.371 kg CO₂ equivalent, respectively (Figure 17). The other LCI impact values were only slightly higher, except for HNCT, which increased significantly (from 2.73 to 8.28 kg 1,4-DCB), due to the installations of PV. Land use in this sensitivity analysis increased roughly 1.8 times when using PV versus conventional electricity. Consequently, locally grown indoor tomatoes powered by PV have a greater land-use impact than imported tomatoes.
Locally grown indoor tomatoes powered by PV had higher impact across all the LCA values. An impact comparison was performed of all three tomato products: 1) conventionally-powered locally grown indoor (used as the base, i.e., scaled at 100%), 2) imported, and 3) PV-powered locally grown indoor (Figure 18). Locally grown tomatoes powered by conventional electricity had the least impact in LU and MU, while imported conventionally grown tomatoes had the least impact in FR, HCNT, HCN, GW, TA and WC. Locally grown tomatoes powered by PV did not have any impact categories with the least contribution of the three models.
Figure 17. A contribution analysis comparison of imported tomatoes and locally grown indoor tomatoes powered by PV in the production of 1 kg tomatoes.
Figure 18. Comparison of potential environmental impact contributions of locally grown indoor tomatoes powered conventionally (as base, i.e. 100%) against imports and those grown locally and powered by PV (in percentages).

Alternative Growing Scenario for Imported tomatoes

In order to test the sensitivity of the growing method for the imported tomatoes, the assumed origin of these tomatoes was changed from conventional production (open field) to heated greenhouse production. For this sensitivity analysis only the tomato production and associated infrastructure was changed, while all other categories connected with acquiring tomatoes (e.g., storage, electricity, freight/shipping, and land transport) were kept constant as both models were assumed that tomatoes were produced in the same region in Italy. The life-cycle impact of the two growing alternatives was compared, with
conventionally grown tomato used as the base (0%) (Figure 19). Again, a negative percentage change implies an improvement in the reviewed sensitivity scenario. The impact from WC, ME, and LU using greenhouse-produced tomatoes is reduced by 30 ppt, 94 ppt, and 48 ppt, respectively. This was mainly due to greenhouses using less land, having a longer production season, and requiring less water due to the recycling mechanism in hydroponics. The impacts of TA, HNCT, HCT, GW, and FRS increase if the imported tomatoes were from a heated greenhouse (Figure 19).

Figure 19. Life-cycle impact comparison when substituting imported conventionally grown tomatoes with heated greenhouse tomatoes (expressed in percent change).

These results may be heavily influenced by data choices and assumptions. When locally grown indoor tomatoes powered by PV are viewed against imported,
conventionally heated greenhouse tomatoes there is a substantial increase in FRS, HNCT, and GW for the heated greenhouse tomatoes (when shifting from conventional to heated greenhouse tomatoes). However, imported heated greenhouse tomatoes still have a lower impact against locally grown indoor tomatoes powered by PV across all life cycle impact categories (Figure 20).

Figure 20. Contribution analysis comparison of imported heated greenhouse tomatoes versus locally grown indoor tomatoes powered by PV in the production of 1 kg of tomato.
Imported heated greenhouse tomatoes and conventionally grown tomatoes dominate the impact assessment of the four models in producing the lowest contribution of the eight impact assessments chosen (Figure 21), using locally grown indoor tomatoes powered by conventional electricity as base (i.e., 100%). The imported heated greenhouse model has the lowest impact in LA, ME, and WC, while the imported conventional tomato has the lowest impact in FR, HCT, HCNT, GW, and TA (Figure 21).

Figure 21. Comparison of potential environmental impact contributions of locally grown indoor tomatoes powered by conventional electricity (as base, i.e., 100%) versus those powered by PV, imported, and (imported) greenhouse-grown (in percentages).
Alternative Transportation Scenario for Imported Greenhouse Tomatoes

Based on conversations with industry professionals along with the head of operations in Madar, air freight was the recommended delivery method since Coeur de Boeuf and Plum tomatoes would deteriorate if shipped by sea. Moreover, greenhouse production of these tomatoes was the most common type of growing method in Europe. Consequently, a sensitivity analysis was conducted to compare the impact of sea freight versus air freight transportation modes for heated greenhouse tomatoes. All other inputs were kept constant. The life-cycle impact of the two delivery alternatives (both grown in indoor heated greenhouses) was compared, using sea shipments as the base (0%); (Figure 22). All of the nine impacts increase substantially due to effects of air freighting the tomatoes.

When air freighted imported heated greenhouse tomatoes are compared with locally grown indoor tomatoes powered by PV there is a substantial increase in FRS, GW, and TA for the air freighted heated greenhouse scenario (Figure 23). For the first time, this causes these impacts to surpass that of the locally grown indoor tomatoes powered by PV (Figure 23).

Air freighted imported heated greenhouse tomatoes have a substantial increase in TA which is illustrated to be the most substantial of all five models assessed (Figure 24); (locally grown indoor tomatoes powered by conventional electricity used as base, i.e., 100%). Another interesting observation is that the air freighted imported heated greenhouse model has the second highest GW impact after locally grown indoor tomatoes. Moreover, as illustrated in Figure 24, shifting locally grown indoor tomatoes employing conventional electricity to that sourced from PV results in a better
performance than that of air freighted imported heated greenhouse. Therefore, again the results suggest that the choice of freight has significant influence on the imported tomato impacts.

Figure 22. Life-cycle impact comparison when substituting sea freighted heated greenhouse tomatoes with air freighted.

Economic Performance of Imported and Locally Grown Indoor Tomatoes

This section covers the total capital expenditure (CapEx), operational expenditure (OpEx), revenue and economic model for both locally grown indoor and imported tomatoes. Lastly, cash flow and projected profitability for both models are compared based on a specified interest rate amortized over a variety of loan schemes and periods.
Figure 23. Comparison of imported greenhouse tomatoes (air freight) versus locally grown indoor tomatoes powered by PV for the production of 1 kg of tomato.
Figure 24. Comparison of potential environmental impact contributions of locally grown indoor tomatoes powered by conventional electricity (as base, i.e., 100%) versus those powered by PV, imported, and (imported) greenhouse-grown sea freight and air freight.

Locally Grown Indoor Tomatoes

The total CapEx to build a 9,000 m² indoor-grown tomato farm is roughly 9 million USD. The indoor facility costs around 2.1 million USD and contributes 23% of the CapEx cost, with 65% of the Capex is accounted for in the indoor facility construction, LED lighting, greenhouse materials, and heating/cooling materials (Table 5).
The total OpEx to produce 380,000 kg of locally grown indoor tomatoes annually is roughly 1.7 million USD. Approximately 61% of this is due to labor and employee costs (Table 6). Moreover, employees represent the highest yearly cost, roughly 910,000 USD, i.e., 54% of total OpEx costs.

Table 5. Capital expenditure for locally grown indoor tomatoes per year.

<table>
<thead>
<tr>
<th>Capital items</th>
<th>Cost (Dirhams)</th>
<th>Cost (US dollars)</th>
<th>% Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Indoor facility construction</td>
<td>7,631,600</td>
<td>2,079,455</td>
<td>22.7%</td>
</tr>
<tr>
<td>Climate control system</td>
<td>2,500,000</td>
<td>681,199</td>
<td>7.4%</td>
</tr>
<tr>
<td>Procurement</td>
<td>932,300</td>
<td>254,033</td>
<td>2.8%</td>
</tr>
<tr>
<td>Hardware and installation</td>
<td>2,956,500</td>
<td>805,586</td>
<td>8.8%</td>
</tr>
<tr>
<td>Regulatory fees</td>
<td>1,166,220</td>
<td>317,771</td>
<td>3.5%</td>
</tr>
<tr>
<td>LED Lighting</td>
<td>5,630,338</td>
<td>1,534,152</td>
<td>16.7%</td>
</tr>
<tr>
<td>Greenhouse materials</td>
<td>5,225,585</td>
<td>1,423,865</td>
<td>15.5%</td>
</tr>
<tr>
<td>Heating and cooling materials</td>
<td>3,808,434</td>
<td>1,037,720</td>
<td>11.3%</td>
</tr>
<tr>
<td>Irrigation materials</td>
<td>1,754,994</td>
<td>478,200</td>
<td>5.2%</td>
</tr>
<tr>
<td>Electric hardware</td>
<td>2,073,479</td>
<td>564,981</td>
<td>6.2%</td>
</tr>
<tr>
<td><strong>Total CaPex</strong></td>
<td><strong>33,679,450</strong></td>
<td><strong>9,176,962</strong></td>
<td>100.0%</td>
</tr>
</tbody>
</table>

Table 6. Operational expenditure for locally grown indoor tomatoes per year.

<table>
<thead>
<tr>
<th>Operational items</th>
<th>Cost (Dirhams/year)</th>
<th>Cost (US dollars/year)</th>
<th>% Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rent</td>
<td>234,000</td>
<td>63,760</td>
<td>3.81%</td>
</tr>
<tr>
<td>Total electricity required</td>
<td>361,350</td>
<td>98,460</td>
<td>5.89%</td>
</tr>
<tr>
<td>Employees</td>
<td>3,336,000</td>
<td>908,992</td>
<td>54.39%</td>
</tr>
<tr>
<td>Water</td>
<td>10,600</td>
<td>2,888</td>
<td>0.17%</td>
</tr>
<tr>
<td>Nutrients</td>
<td>25,379</td>
<td>6,915</td>
<td>0.41%</td>
</tr>
<tr>
<td>Seeds</td>
<td>223,000</td>
<td>60,763</td>
<td>3.64%</td>
</tr>
<tr>
<td>Packaging</td>
<td>766,000</td>
<td>208,719</td>
<td>12.49%</td>
</tr>
<tr>
<td>Labor</td>
<td>439,200</td>
<td>119,673</td>
<td>7.16%</td>
</tr>
<tr>
<td>Transportation</td>
<td>80,000</td>
<td>21,798</td>
<td>1.30%</td>
</tr>
<tr>
<td>Consumables</td>
<td>539,696</td>
<td>147,056</td>
<td>8.80%</td>
</tr>
<tr>
<td>CO2 (carbon dioxide)</td>
<td>118,625</td>
<td>32,323</td>
<td>1.93%</td>
</tr>
<tr>
<td><strong>Total OpEx</strong></td>
<td><strong>6,133,850</strong></td>
<td><strong>1,671,349</strong></td>
<td>100.00%</td>
</tr>
</tbody>
</table>
The revenue for an indoor farm is around 3,350,000 USD annually (Table 7). This is based on Madar Farms selling their tomatoes as wholesale.

Table 7. Yearly revenue for locally grown indoor tomatoes.

<table>
<thead>
<tr>
<th>Cost (Dirhams/year)</th>
<th>Cost (US dollars/year)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total Revenue</td>
<td>12,292,500</td>
</tr>
</tbody>
</table>

An economic model for locally grown tomatoes with an interest rate of 3%, amortized over 24 quarters (six years), was developed to depict the profit and loss (P&L) of locally grown tomatoes (Figure 25). Plot A (of Figure 25), shows the utilization factor for each quarter. It was assumed to be zero in Quarter (Q) 1, since the farm is yet to be built, and gradually increase to 0.95 in Q7, and thereafter stays constant. The utilization factor does not exceed 0.95 throughout the six years, in order to take 5% losses into account, an assumption similar to other studies (Eaves & Eaves, 2018). Plot B shows the investment needed each quarter, equal to the total CapEx (Table 5) amortized over 24 quarters with an interest of 3%, a rate assumption based on a literature review and an interview with Madar Farm (Wagner, 2019). Plot C portrays the OpEx profit, which is the revenue (Table 7) per quarter (3,349,455 divided by four) multiplied by the utilization factor. The OpEx profit starts from zero, since the utilization factor in quarter one is zero, reaching a maximum of 398,550 USD on Q7 and remaining constant till Q24, since the utilization factor is 0.95. Plot D is the net quarterly income, i.e., the addition of investment and OpEx profit (Plots B and C). Lastly, Plot E shows cumulative net income, or the accumulation (successive additions) of the net income (Plot D). The cumulative net income is constantly decreasing, reaching negative 1,839,210 USD, mainly due to the
high CapEx cost of 9,176,962 USD. Lastly, it is important to note that if the farm has access to governmental subsidies. This would change the projections and lead to quicker path to profitability.

Although a 6-year loan of the CapEx amortized over 24 quarters portrays a cumulative loss to an indoor tomato business, depicting a variety of loan periods over 15 years provides another picture (Figure 26). It takes the 4-year loan roughly 7 years (Q4 of the 7th year to be specific) to have a positive net cumulative income as opposed to the 15 year loan, which has a positive net cumulative income in year 2 (Q3 of the 2nd year to be specific) (Figure 26). Over 15 years, however, the 4-year loan would have a larger net cumulative income than the 15-year loan, ~ 12,797,600 USD and 11,140,600 USD (~1,657,000 USD difference), respectively. This is due to the 3% loan being amortized over a longer period.
Figure 25. Economic model for locally grown tomatoes over 6 years (shown as quarters).
Plot A: utilization factor; Plot B: investment; Plot C: OpEx profit; Plot D: net income;
Plot E: Cumulative Net Income.
Figure 26. Cumulative net income for a variety of loan schemes over a 15-year period at 3% interest for locally grown indoor tomatoes.

Imported Tomatoes

The total CapEx for the imported tomatoes model is primarily related to the 4 x 4 x 3 m cold storage unit, costing roughly 6,000 US dollars (Table 8).
Table 8. Capital expenditure for imported tomatoes per year.

<table>
<thead>
<tr>
<th></th>
<th>Cost (Dirhams)</th>
<th>Cost (US dollars)</th>
<th>% Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Storage facility</td>
<td>23,000.00</td>
<td>6,267.03</td>
<td>100.0%</td>
</tr>
<tr>
<td><strong>Total CaPex</strong></td>
<td><strong>23,000.00</strong></td>
<td><strong>6,267.03</strong></td>
<td><strong>100.0%</strong></td>
</tr>
</tbody>
</table>

The total OpEx to import 380,000 kg of indoor-grown tomatoes (air freighted) for a year is roughly 3 million US dollars. The import of two types of tomatoes, Coeur de Boeuf and Plum, is roughly 2.5 million USD, which amounts to 82% of the total OpEx cost (Table 9). An important point to note is that the import costs includes all logistics, freight, clearance, demurrage, and port charges.

Table 9. Operational expenditure for imported tomatoes per year.

<table>
<thead>
<tr>
<th></th>
<th>Cost (Dhs/year)</th>
<th>Cost ($/year)</th>
<th>% Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Land</td>
<td>520.00</td>
<td>141.69</td>
<td>0.005%</td>
</tr>
<tr>
<td>Coeur de Boeuf Import</td>
<td>7,750,000.00</td>
<td>2,111,716.62</td>
<td>70.9%</td>
</tr>
<tr>
<td>Plum tomatoes import</td>
<td>1,314,000.00</td>
<td>358,038.15</td>
<td>12.0%</td>
</tr>
<tr>
<td>Labour</td>
<td>200,000.00</td>
<td>54,495.91</td>
<td>1.8%</td>
</tr>
<tr>
<td>Employees</td>
<td>816,000.00</td>
<td>222,343.32</td>
<td>7.5%</td>
</tr>
<tr>
<td>Electricity</td>
<td>5,256.00</td>
<td>1,432.15</td>
<td>0.05%</td>
</tr>
<tr>
<td>Packaging</td>
<td>766,000</td>
<td>208,719</td>
<td>7.0%</td>
</tr>
<tr>
<td>Transportation</td>
<td>80,000</td>
<td>21,798.37</td>
<td>0.7%</td>
</tr>
<tr>
<td><strong>Total OpEx</strong></td>
<td><strong>10,931,776</strong></td>
<td><strong>2,978,685.56</strong></td>
<td><strong>100.0%</strong></td>
</tr>
</tbody>
</table>

The revenue for the imported tomato business model is around 3,595,436 USD a year, based on imported tomatoes being sold 50% to restaurants and the other 50% being distributed/traded (Error! Not a valid bookmark self-reference.).
Table 10. Yearly revenue for imported tomatoes.

<table>
<thead>
<tr>
<th>Total Revenue</th>
<th>Cost (Dirhams/year)</th>
<th>Cost (US dollars/year)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>13,195,250</td>
<td>3,595,436</td>
</tr>
</tbody>
</table>

An economic model for imported tomatoes with a 3% interest rate amortized over 24 quarters (six years) was developed to understand/depict the profit and loss (P&L); (Figure 27). The utilization was assumed to be 0.98 (2% loss) for the entire period since the import model starts to become fully operational from the first quarter (Plot A, Figure 27). Plot B shows the investment needed each quarter, which is equal to the total CapEx (Table 8) amortized over 24 quarters with an interest of 3%. The capital expenditure is ~417 USD per quarter, which is diminished in comparison to the locally grown indoor tomato model, where CapEx is 419,247 USD per quarter. Plot C portrays the OpEx profit, which is the revenue (The revenue for the imported tomato business model is around 3,595,436 USD a year, based on imported tomatoes being sold 50% to restaurants and the other 50% being distributed/traded (Error! Not a valid bookmark self-reference.). Table 10) per quarter (3,595,436 divided by 4) multiplied by the utilization factor. The OpEx profit starts from the first quarter, since the utilization factor in quarter one is 0.98. Plot D represents the net quarterly income, i.e., the addition of investment and OpEx profit (Plots B and C). Last, plot E shows the cumulative net income, i.e., the successive addition of the net income (Plot D). This model has a positive commutative net income from quarter 1 (1,156,168 USD) that increases quarterly, reaching 3,747,795 USD in Q24 (6th year). Since the CapEx cost for this model is minimal, this business
model is seen as profitable from the first quarter as opposed to that for locally grown tomatoes.

In the previous section, a 6-year loan of the CapEx amortized over 24 quarters demonstrated a cumulative profit for the imported tomatoes business. Furthermore, evaluating a variety of loan periods over 15 years projects a similar result (Figure 28).
Figure 27. Economic model for imported tomatoes over 6 years (shown as quarters). Plot A: utilization factor; Plot B: Investment; Plot C: OpEx profit; Plot D: net income; Plot E: cumulative net income.
Figure 28. Cumulative net income for various loan schemes over a 15-year period at 3% interest for imported tomatoes.

Since the tomato importing business is not CapEx heavy, 6,267 USD total, the different loan schemes affect neither the financials nor cash flow of the business. Nevertheless, over 15 years, the 4-year loan would have a larger net cumulative income than the 15-year loan, 937,9993 USD and 9,378,861 USD (1,312 USD difference), respectively, which is due to a 3% loan being amortized over a longer period.

Business Model Tomatoes Comparison: Imported Versus Locally Grown Indoor Tomatoes

A 10-year loan period projected over 15 years shows that imported tomatoes would be more profitable in the first 12 years, after which (year 13, Q2)
grown tomato business shows greater profitability over the lifetime of the business (Figure 29). Furthermore, this model reaches a cumulative net income of 11,914,184 USD at the end of year 15, as opposed to 9,379,390 USD for imported tomatoes, or roughly a 2.5 million USD increase in the cash flow for the locally grown tomato business.

![Cumulative Net Income Comparison](image)

**Figure 29.** 15-year period cumulative income comparison between imported and locally grown indoor tomatoes based on a 10-year loan at 3% interest.

A 15-year loan period projected over 15 years shows that imported tomatoes would be more profitable in the first 7 years, after which (year 7 Q 2) a model for a locally grown tomato business shows greater profitability over the lifetime of the business (Figure 30). Furthermore, the locally grown tomato business model reaches a
cumulative net income of 11,140,612 USD in the end of year 15, as opposed to 9,378,861 USD for imported tomatoes, resulting in a roughly 1.7 million USD increase in the cash flow for the locally grown tomato business. The difference between both models’ cash flow shrank from 2.5 million USD in the 10 year-loan period to 1.7 million dollars in the 1r year-loan period due to the 3% interest being amortized over a longer period (15 versus 10 years).

Figure 30. 15-year period cumulative income comparison between imported and locally grown indoor tomatoes based on a 15-year loan at 3% interest.
Chapter IV

Discussion

This thesis used economic and environmental performance assessments to compare the practice of locally growing indoor tomatoes versus importing them. A life-cycle assessment of an economic model provided data with which to visualize and analyse an initial hypothesis that indoor farming has a smaller environmental impact and represents a more cost-effective business when compared to the importing of tomatoes to the UAE. Drawing upon my findings, I will:

- evaluate the advantages and disadvantages of both methods and compare them against previous studies,
- provide ideas and recommendations regarding indoor farming technology as applied to growing tomatoes,
- discuss public policy measures that might be taken by the governments of the UAE and those of its neighboring countries to reach the goal of food security, and
- finally, I will summarize the conclusions of this study, discuss research limitations, and give recommendations for future research on indoor farming methodologies.

LCA Results Interpretation

Although I predicted initially that growing indoor tomatoes locally would be more “environmentally friendly” than importing them, I did not expect the method to show
promising results in only three (FRC, GW and TA) of the eight chosen impact categories (LU, FRS, HNCT, HCT, GW, TA, ME, and WC) for the comparison mentioned above.

Taking a closer look at the inputs to locally grown tomatoes produced by indoor farming, the results indicated that the largest potential impact stemmed from electricity, contributing over 50% in five of eight impact categories (LU, FRS, HCT, GW, and TA) and having a highest contribution toward global warming (GW), 96%. Waste and water usage had high contributions in HNCT, ME, and WC. Analyzing the different sources of electricity used for an indoor farm showed that heating and cooling systems consumed the largest share, roughly 81% of the total electricity used.

Perhaps the most surprising result of this study was finding that water consumption (WC) is higher for locally grown indoor tomatoes than for imported, conventionally grown tomatoes. Advocates for indoor farming usually claim that hydroponics systems consume between 80-95% less water (Cooper, 2013; Dastoor, n.d; Al-Kodmany, 2018). None of these studies, however, looked at the amount of water needed throughout the entire growth life cycle but only at the direct water consumption in the farm. A closer look at water consumption in indoor tomato farming revealed that electricity contributes to roughly the same amount of WC as irrigation water (Figure 31), underscoring the fact that electricity has a major role in any impact assessment of indoor tomato farming, due to UAE’s electricity production system.

Certain studies may have different results reflecting the type of electricity used and the facility being built. For example, Muñoz et al. (2008) developed an LCA for tomatoes produced in greenhouses versus those from open fields in Catalonia, Spain, finding that the WC in greenhouses is half of that of open-field grown tomatoes. However, this result

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can be linked to the region (Spain) type of facility, i.e., a greenhouse, and the electricity mix used in Spain (Muñoz et al., 2008).

Figure 31. Percent contribution of inputs for water consumption to produce 1 kg of locally grown indoor tomatoes.

Sensitivity Analysis

Since electricity was a chief contributor to the bulk of impact assessments chosen, a first-order sensitivity analysis on the choice of electricity mix was reviewed. For indoor tomatoes, each kg of tomato produced required 21 kWh of electricity, a quite substantial
number mainly due to the cooling loads of indoor farming. For the LCA, the electricity used for indoor farming was of conventional medium voltage level produced in the UAE (Ecoinvent LCI dataset: market for electricity, medium voltage | electricity, medium voltage | Cutoff, S-AE). Once it was substituted for with PV (Ecoinvent LIC dataset: electricity production, photovoltaic, 3kWp flat-roof installation, multi-Si | electricity, low voltage | Cutoff, S-ROW) there was a substantial improvement in GW, FRS in which each showed decreases of 83 and 90 ppt when compared with conventional electricity. The remaining six impact categories WC, TA, ME, LU, HNCT, HCT resulted in increased impacts, however. Although a conclusion would be that PVs can bring clean energy by decreasing GW, their use has many related environmental implications due to the material sourcing and space needed to be occupied by them (Meier, 2002).

The second-order sensitivity analysis treated an alternative growing scenario for imported tomatoes by comparing conventionally grown tomatoes to those from a heated greenhouse. For the LCA, the conventionally grown tomatoes (Ecoinvent LCI dataset: tomato production, processing grade, open field | tomato, processing grade | Cutoff, S) were substituted for heated greenhouse tomatoes (Ecoinvent LIC dataset: tomato production, fresh grade, in heated greenhouse | tomato, fresh grade | Cutoff, S). Results showed that WC, ME, and LU had improved with the heated greenhouse model due to increased output and water recycling mechanisms using hydroponics in the greenhouses. At the same time, the impact categories TA, HNCT, HCT, GW, and FRS had an increase in potential negative impacts.

A comparison of the five models, i.e., locally grown indoor tomatoes powered conventionally (as base, i.e., 100%) versus those powered by PV, conventionally grown
imported tomatoes, and heated greenhouse grown imported tomatoes with air or sea freighted mode of transportation, is shown in Figure 24. For LU, imported heated greenhouse tomatoes had the lowest contribution, 47% less than locally grown tomatoes using conventional electricity. The main reason behind the difference is found to be the electricity usage, which contributed to 55% of the land use in locally grown tomatoes. The impact categories FRS, HCNT, and HCT have the lowest contribution in conventionally imported tomatoes. Electricity still had the largest contribution for the impact categories FRS and HCT for both conventional and PV-provided energy growing methods. Regarding HCT, waste was the main contributor. As for locally grown indoor tomatoes (powered by PV), the production process had the highest contribution for all the impact categories, LU, HCT, HCNT, ME, and WC. Conventionally imported tomatoes have the lowest TA, electricity once again playing a big role in both conventionally and PV-powered indoor farms, 83% and 86%, respectively, of the contribution. ME is a quite substantial factor in both imported conventionally grown tomatoes and indoor tomatoes powered by PV due to the processes of water runoff and PV construction, respectively. Lastly, WC was lowest for imported heated greenhouse tomatoes (sea freighted). This could be partly due to the hydroponics technology and the source of electricity in Italy not requiring much water.

GW is one of the most crucial impact areas that studies examine. It sums the amount carbon dioxide (CO₂), methane (CH₄), nitrous oxide (NO₂), and refrigerant gases and translates them in order to be expressed as carbon dioxide equivalent (CO₂e). A tonne of carbon is roughly the same as burning petrol in two standard garden water butts (Berners-Lee, 2010). On average a UK citizen emits 15 tonnes of GHG emissions, a
number lower than for Americans and Australians but higher than for Chinese and Malawians (Berners-Lee, 2010).

In this research, 1 kg of imported conventionally grown tomatoes sea freighted had the lowest greenhouse gas emission contribution, 0.41 kg CO$_2$-eq, followed by: imported heated greenhouse tomatoes, 1.3 kg CO$_2$-eq, locally grown indoor tomatoes powered by PV, 2.1 kg CO$_2$-eq, and imported greenhouse tomatoes air freighted, 6.9 kg CO$_2$-eq (all numbers are based on 1 kg of commercial production). Finally, locally grown indoor tomatoes using conventional electricity had the highest greenhouse gas emission, 11.9 kg CO$_2$-eq, roughly 5.7 times more than those from indoor farms powered by PV, fully justifying the advantages of shifting the source of electricity to PV.

It is important to note that based on discussions with Madar farms, the sensitivity analysis of alternative transportation scenarios for imported greenhouse tomatoes, which compares air freighted imported greenhouse tomatoes with locally grown tomatoes powered by PV, would have been the baseline assumption. Based on the research they have conducted; the majority of Coeur de Boeuf and Plum tomatoes are air freighted to the UAE in order to preserve the freshness of the product.

Economical Model Interpretation

The CapEx of importing tomatoes, 6,000 USD, was dwarfed in comparison to that of indoor-grown tomato farm at 9,000,000 USD. For these investments, roughly 2.1 million USD went for the indoor construction and 1.5 million USD for LED lighting, both contributing to around 40% of the total CapEx. On the other hand, the import model merely required a cold storage facility for its CapEx.
In contrast, the OpEx cost was marginal for indoor-grown tomatoes (1.7 million US dollars) compared to that of the import model (roughly 3 million US dollars). The main reason for this difference is that the import model has a high cost attributed to the import of tomatoes, or roughly 71% of the total OpEx.

Based on the assumptions that locally grown tomatoes will be entirely sold in the wholesale market and the imported tomatoes will be sold to restaurants (50%) and distributors (50%), the resulting revenues would be 12.3 and 13.2 million USD, respectively.

Using a mix of 3% interest loan periods for capital of 4, 6, 8, 10, and 15 years for both models, showed that locally grown indoor tomatoes had a much higher variability of cumulative net income, reflecting the high CapEx cost, making that model profitable in year 7 Q4, year 8 Q1, year 5 Q2, year 3 Q3, year 2 Q3, respectively. Loan periods longer than eight years had a faster path for profitability. One caveat to this, however, is that cumulative net income also decreases; e.g., for a 4-year loan period, the cumulative net income would be 12.8 million USD at year 15 as opposed to 11.1 million USD for a 15-year loan. Thus, there is a cost opportunity for having either a short or a long-term loan; shorter loans project higher profitability in the future but require a longer period to become profitable, and vice versa for loans of longer term. On the other hand, imported tomatoes have little variance in the area of cumulative net income due to the small CapEx cost (6000 USD) and are profitable from year 1 Q1. A four-year loan has a slightly higher cumulative net income versus 15-year loan, a difference of around 1,000 USD.

Ten- and fifteen-year financial approaches developed for both models using a 3% amortized interest rate revealed that relying on locally produced indoor tomatoes is more
profitable than buying imported tomatoes, 2.5 and 1.7 million USD difference between the two models, respectively. The difference shrinks over the loan periods (10 and 15) due to the interest rates.

Comparison with Other Studies

A large proportion of LCA studies have looked at greenhouses separately. Furthermore, researchers have used dissimilar impact categories and datasets from the present ones; hence, for this section I discuss the most commonly employed impact category, greenhouse gas emissions (GW). A study performed Hendricks and Van Acker (2012) on greenhouse-produced tomatoes in Ontario demonstrated an average yield of 56.4 kg tomato/m², as compared to 42.5 kg tomato/m² for this study. The authors used Ecoinvent inventory, and their specific datasets and assumptions were different (geographically) than those used in this research. They concluded the greenhouse gas emissions to be roughly 2.9 kg CO₂-eq per kg of tomatoes. A second study in Finland compared indoor farming using LED lights with greenhouses powered by sunlight, inserting a production break during the coldest and darkest part of a year (November-February), and concluded GW to be roughly ~5 to 6.4 and 0.8 to 4.7 kg CO₂-eq per kg of tomatoes, respectively, based on data from the Statistical Centre of Finland and interviews with conventional producers (Keskitalo, 2009). A comparison of multi-tunnel greenhouse production in Spain, Hungary, and the Netherlands reported GHG emissions of roughly 0.28, 0.49, and 0.9 kg CO₂-eq per kg of tomato (Torrellas et al., 2012).

Two other studies compared greenhouse-produced tomatoes versus conventionally produced ones. Greenhouse tomatoes in Catalonia, Spain, produced GW of 0.0744 kg
CO$_2$-eq per kg of tomato and WC of 0.024 m$^3$ (Muñoz et al., 2008), whereas a study of greenhouse tomatoes from Iran found a GW of 0.050 kg CO$_2$-eq per kg of (Zarei, Kazemi, & Marzban, 2019).

These studies showed a large variance in reported GHG emissions, ranging from 0.065 to 6.4 kg CO$_2$-eq per kg of tomato. The striking variability within the results is likely attributed to geographical location, type of facility (fully indoor-powered by LED, greenhouse-powered by LED, or greenhouse-powered by sunlight), and the electricity mix used to power these farms, all of which plays a big role in determining GW impact. Moreover, the choice of dataset (e.g., Ecoinvent and ThinkStep) and LCI data chosen for the LCA analysis exerts a strong effect on the variability of the results. Comparing these studies with the present one would not be a logical approach; rather, researchers should study the specific impact found at different facilities in the UAE.

One study based on the literature reviewed looked at the economic impact of greenhouse growing compared to the use of vertically (stacked) farms for the production of lettuce (Eaves & Eaves, 2018). The greenhouse had a CapEx of 480,060 USD, an OpEx of 231,317 USD, and a revenue of 476,637 USD, resulting in a gross profit of 184,920 USD. The vertical farm, on the other hand, had a CapEx of 587,526 USD, an OpEx of 208,382 USD, and a revenue of 476,637 USD, resulting in a gross profit of 194,334 USD (Eaves & Eaves, 2018). While that study was based on lettuce, to get an idea of how it differs to the indoor tomato farm in this research, the vertical farm CapEx and OpEx showed indoor tomato farm revenues to be 16 and 8-fold higher, respectively.
Research Recommendations

The contemporary indoor farm utilizes a single vertical dimension (no stacking) for tomato growing. If a farm shifted to a stacked model (tomatoes stacked on top of each other), it could decrease its negative environmental impact and increase its profitability. Since electricity is one of the main inputs that contributes to a majority of impacts of the system, introducing stacking to an indoor farm will result in using the same amount of space but a decrease of overall electricity (however not by a substantial amount according to Madar farms), thus lessening the environmental impact because the production output should roughly double (in the case of two stacks). Moreover, from an economic standpoint stacking in the indoor farm can become even more profitable by reaching economies of scale since production will increase and become more efficient while lowering costs mainly due to utilizing the same amount of land and space. There will be a additional CapEx involved for constructing the 2nd layer of tomato farming, LED lights, and a change of foundation; however, most the remaining CapEx cost would stay constant. Furthermore, OpEx will increase by a small percentage from more efficient labor (due to economies of scale even though the labor force may need small augmenting). Moreover, the farm’s annual production of tomatoes will double or triple, depending on the number of stacks, thus doubling/tripling revenues.

Another recommendation for the indoor farming model is to shift from being a wholesale tomato retailer to becoming a grower in control of its own logistics with a similar selling model (restaurants and distributors) to that of imported tomatoes. A shift to its own logistics would result in an increase in the indoor farm’s revenue by more than 7% (greater than 13.2 million USD). Further, the produce could be marketed as local,
fresh and sustainable, consequently having a competitive selling advantage over imported produce (Soliman, 2019; Lang & Barling, 2013; Hempel & Hamm, 2016). It’s important to note, that a shift to own logistics is usually dependent on the scale of production of a farm. This might not be plausible in the farms first phase, but nevertheless it should be definitely considered and analyzed.

Research on indoor farm lighting has been a hot topic in recent years. Studies on smart illumination system (ILSys) which control the LED light systems and emit pulsed lights have shown higher efficiencies in the photosystem (Olvera-Gonzalez et al., 2013). In addition, control of pulse timing of red and blue has proved important in cultivation of tomatoes (Shimada & Taniguchi, 2011). Lastly, a variety of studies have looked into different lightning technologies that decreases overall electricity costs (Van Iersel & Gianino, 2017; Ahn, Bae, & Kang, 2017). If the farm utilizes and stays up to date with current research, or adopts a research facility to experiment on a variety of these topics, it can increase its tomatoe yield and decrease the costs of electricity.

Public Policy Recommendations

There is no question that the Covid-19 pandemic has affected the international flow of produce. Many countries are opting to reserve their produce instead of exporting, consequently triggering warnings from U.N. food agency leaders about disruptions to the global food supply (Dixon, Stern & Kumenov, 2020). Furthermore, a loss in agricultural work together with supply-chain disruptions will affect import-dependent countries (Milman, 2015; Corkery & Yaffé-Bellany, 2020). It is becoming imperative for those governments heavily reliant on produce imports to start taking a path to self-sustainable locally produced foodstuffs (Jonathan et al., 2011; Vermeulen et al., 2012). Food security
has been an important recent topic of conversation, especially within countries of harsh climates (cold or warm). Policy makers should start addressing these issues and strategically plan on adopting varied indoor farming technologies in order to complement their future food imports.

The indoor farm model in this research has been demonstrated to be more economical than the imported food model. Therefore, it may now be incumbent upon governments to encourage locally producing foodstuff by investing in start-ups, creating farm subsidies to encourage the ecosystem to thrive, and by committing research funds to advance these efforts in their respective countries.

Yet another reason for highlighting the importance of locally grown produce is the current political instability around the UAE (BBC, 2020; CNN, 2017). Embargoes and wars can affect its food supply. The country could work around this by investing in domestic farming industries and also creating government-run farms in order to decrease food imports and achieve sustainability goals. A leading example could be the Netherlands, a quite a small and densely populated country of roughly 1,300 inhabitants per square mile, which had ambitious sustainable agriculture targets in the early 2000s. After achieving many of these targets, the Netherlands has become the 2nd largest exporter of vegetables in terms of value, just after the US, which is 237 times larger (Treat, 2018). Eighty percent of the cultivated land in the Netherlands is under greenhouse cultivation (TheCivilEngineer.org., 2018); (Figure 32). If the UAE had a similar commitment to sustainable agriculture, it might not only reach self-sufficiency, but start becoming a net exporter of produce.
Figure 32. Greenhouses surrounding a farmer's home in the Netherlands.

Conclusions

This research has identified key factors determining the success of indoor tomato farms from both an economic and environmental viewpoint. The study is one of the first of its kind in the region and can kickstart the research into new technologies. Moreover, the UAE Ministry of Climate Change can employ this study to understand the environmental impact of locally grown indoor tomato production in the UAE. Consequently, the UAE government would be able to make informed economic and strategic public policy decisions regarding local tomato production. Finally, this study can be used in the future to look at other types of produce and various other methods of controlled-environment agriculture.
Research Limitations

As this study is the first of its kind in the region, there were some inevitable limitations. The thesis focused on two main comparisons. The first was related to the environmental assessment of importing tomatoes versus locally growing indoor tomatoes under controlled conditions. The choice of datasets in the LCA, i.e., specific datasets from Ecoinvent used for this research, can lead to different results, therefore, causing some inconsistencies and limitations. Because only limited data is available for the region reviewed, i.e., the UAE, this research tried to utilize the rest of the world (ROW) or global (GLO) data as much as possible; in some instances, the UAE dataset was used, for example, the market for electricity, medium voltage | electricity, medium voltage | Cutoff, S-AE. Processing grade, open field | tomato, processing grade | Cutoff, S LCI dataset was utilized for the imported tomatoes which is not the most accurate estimate since these kind of tomatoes would entail lower quality varieties with completely different nutrient energy requirements, than the ones produced in the indoor farm. Furthermore, The ReCipe method that was employed is usually based on European or global data which can bias the results. Eight LCA impacts were chosen of the 18 available in the Ecoinvent dataset, but other environmental impacts were not discussed in this research. Lastly, within any LCA study there is always uncertainty in the results which needs to be taken into consideration when making conclusions or decisions.

The second focus of the research was to build economic models for both imported tomatoes and locally grown indoor tomatoes (under controlled conditions) and compare the associated financials over a 15-year period. There were two main limitations to this. The first is that because this farm was not operational (currently being built), the data was
acquired through a literature review, interviews with industry professionals, and from discussions with the Head of Operations and the Head of Sales and Logistics at Madar Farms. There is usually variation, however, between modeled data and the real-life performance of operational farms due to factors not being accounted for. This will cause some deviation between the true costs and profits. Second, there were several assumptions made, for example, regarding yearly crop production (yields in kg/m²-yr), revenue/prices of produce (USD/kg), startup capital costs of indoor farms (USD), operational costs (USD), and risk/losses (yield).

In summary, the results and conclusion presented above are limited to the assumptions, datasets utilized, the environmental impacts selected, and the analysis done in this research. In order to come up with public policy actions, more comprehensive studies could certainly be done on the myriad types of technologies and their costs and benefits, to complement this study.

Recommendations for Futures Studies

This study was based on a high-tech indoor farm. Future studies should look into other types of farming, such as greenhouse or lower-tech indoor farms, and compare such against the models developed in this research. A sensitivity analysis can also be performed to look at the different tomato sale prices and risk of produce losses. Moreover, once the farm is operational, a study might compare the assumptions used in this study against any actual environmental impact, capital and operational expenditures, revenue, and profits. As for the LCA model, future studies could consider other datasets as well as other environmental effects, comparing these against this thesis’s results.
Future research should also look at the percentage decrease in environmental impacts and increase in profitability once stacking of tomatoes is utilized in the same amount space (used in this research). Finally, an uncertainty analysis using Monte Carlo simulation might be utilized in future studies to understand the variability of the data.
Appendix

Life Cycle Inventories and Assessments

Table 11. Life cycle inventory for indoor-grown indoor tomatoes.

<table>
<thead>
<tr>
<th>Process/Input</th>
<th>Name</th>
<th>LCI Dataset</th>
</tr>
</thead>
<tbody>
<tr>
<td>Infrastructural</td>
<td>Greenhouse</td>
<td>Greenhouse construction, glass walls and roof, metal tubes</td>
</tr>
<tr>
<td></td>
<td>LED</td>
<td>Market for light emitting diode</td>
</tr>
<tr>
<td>Raw Materials</td>
<td>Seeds</td>
<td>Tomato seedling production, in heated greenhouse, for planting</td>
</tr>
<tr>
<td></td>
<td>Nitrogen (N)</td>
<td>Market for nitrogen fertiliser, as N</td>
</tr>
<tr>
<td></td>
<td>Phosphore (P)</td>
<td>Market for phosphate fertiliser, as P2O5</td>
</tr>
<tr>
<td></td>
<td>Potassium (K)</td>
<td>Market for potassium carbonate</td>
</tr>
<tr>
<td></td>
<td>Rockwool</td>
<td>Stone wool production</td>
</tr>
<tr>
<td></td>
<td>Water</td>
<td>Tap water production, seawater reverse osmosis, conventional pretreatment, baseline module, single stage</td>
</tr>
<tr>
<td>Energy Inputs</td>
<td>Lightning</td>
<td>Market for electricity, medium voltage</td>
</tr>
<tr>
<td></td>
<td>Heating and cooling</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Ventilation</td>
<td></td>
</tr>
<tr>
<td>Transportation</td>
<td>Aircraft transport of seedlings</td>
<td>Transport, freight, aircraft, intercontinental</td>
</tr>
<tr>
<td></td>
<td>Land transport of tomatoes</td>
<td>Transport, freight, lorry with refrigeration machine, 3.5-7.5 ton, EURO5, carbon dioxide, liquid refrigerant,</td>
</tr>
<tr>
<td>Outputs</td>
<td>Waste</td>
<td>Treatment of municipal solid waste, sanitary landfill</td>
</tr>
</tbody>
</table>

Table 12. Life cycle Inventory for imported tomatoes.

<table>
<thead>
<tr>
<th>Process/Input</th>
<th>Name</th>
<th>LCI Dataset</th>
</tr>
</thead>
<tbody>
<tr>
<td>Conventional Tomato Production</td>
<td>Locally produced tomatoes</td>
<td>Tomato production, processing grade, open field</td>
</tr>
<tr>
<td>Energy Inputs</td>
<td>Cooling</td>
<td>Market for electricity, medium voltage</td>
</tr>
<tr>
<td>Transportation</td>
<td>Maritime transport of tomatoes</td>
<td>Market for transport, freight, sea, transoceanic ship with reefer, freezing</td>
</tr>
<tr>
<td></td>
<td>Land transport of tomatoes</td>
<td>Transport, freight, lorry with refrigeration machine, 3.5-7.5 ton, EURO5, carbon dioxide, liquid refrigerant,</td>
</tr>
<tr>
<td>Outputs</td>
<td>Waste</td>
<td>Treatment of municipal solid waste, sanitary landfill</td>
</tr>
</tbody>
</table>
Table 13. Life cycle inventory for sensitivity analysis.

<table>
<thead>
<tr>
<th>Process/Input</th>
<th>LCI Dataset</th>
</tr>
</thead>
<tbody>
<tr>
<td>Photovoltaics (PV)</td>
<td>Electricity production, photovoltaic, 3kWp flat-roof installation, multi-Si</td>
</tr>
<tr>
<td>Heated Greenhouse</td>
<td>Tomato production, fresh grade, in heated greenhouse</td>
</tr>
</tbody>
</table>

Table 14. Life-cycle assessment of producing 1 kg of imported tomatoes.

<table>
<thead>
<tr>
<th></th>
<th>LU (m2a crop eq)</th>
<th>FRS (kg oil eq)</th>
<th>HNCT (kg 1,4-DCB)</th>
<th>HCT (kg 1,4-DCB)</th>
<th>GW (kg CO2 eq)</th>
<th>TA (kg SO2 eq)</th>
<th>ME (kg N eq)</th>
<th>WC (m3)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Field tomatoes from</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Italy</td>
<td>6.29E-03</td>
<td>3.17E-02</td>
<td>2.00E-01</td>
<td>5.91E-03</td>
<td>1.27E-01</td>
<td>7.50E-04</td>
<td>2.30E-04</td>
<td>2.40E-02</td>
</tr>
<tr>
<td>Storage Electricity</td>
<td>1.37E-05</td>
<td>1.55E-02</td>
<td>3.29E-03</td>
<td>1.95E-04</td>
<td>3.74E-02</td>
<td>2.20E-05</td>
<td>8.17E-08</td>
<td>7.00E-05</td>
</tr>
<tr>
<td>Shiping</td>
<td>3.40E-04</td>
<td>5.70E-02</td>
<td>4.46E-02</td>
<td>4.48E-03</td>
<td>1.83E-01</td>
<td>2.29E-03</td>
<td>1.73E-06</td>
<td>4.77E-04</td>
</tr>
<tr>
<td>Land transport of</td>
<td>1.04E-03</td>
<td>2.00E-02</td>
<td>3.01E-02</td>
<td>1.79E-03</td>
<td>6.10E-02</td>
<td>1.52E-04</td>
<td>6.05E-07</td>
<td>1.69E-04</td>
</tr>
<tr>
<td>tomatoes</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>7.68E-03</strong></td>
<td><strong>1.24E-01</strong></td>
<td><strong>2.78E-01</strong></td>
<td><strong>1.24E-02</strong></td>
<td><strong>4.08E-01</strong></td>
<td><strong>3.21E-03</strong></td>
<td><strong>2.32E-04</strong></td>
<td><strong>2.47E-02</strong></td>
</tr>
</tbody>
</table>
References


Frommer, D. (2014). This indoor farm in Japan used to be a floppy disk factory. Retrieved from https://qz.com/295936/toshibas-high-tech-grow-rooms-are-churning-out-lettuce-that-never-needs-washing/


Keskitalo, Antti. (2009). Environmental impacts of conventionally and year-round produced greenhouse tomato (Solanum lycopersicum L.) Production Chain in Finland.


Madar Farms. (2020). We are here to help tackle food and water security challenges in the region. Retrieved from https://www.madarfarms.co/

Meier, Paul. (2002). Life-cycle assessment of electricity generation systems and applications for climate change policy analysis.


Nexus. (2018). Water-energy-food in the United Arab Emirates (pp. 8-10, Rep.).


Project, T. (n.d.). Aquaponics is the way food will be grown in the future, starting now. Retrieved from http://tucsonap.org/


