Innovation through alternative enterprises: The case of water management and producer incomes in Southwest Kansas

by

Gyventzly Gayaver Eugene

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Approved by:

Major Professor
Dr. Vincent Amanor-Boadu

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Abstract

The depletion of the Ogallala Aquifer presents an existential threat to the agricultural economy of southwest Kansas. Decades of conservation efforts, including improved irrigation efficiency, crop switching, and groundwater governance seem to have failed to arrest the threat. This research reframes the problem by shifting the focus from water conservation to income preservation. It assesses the economic feasibility of producing hydroponic greenhouse tomatoes in an area without a history of such production with the objective of preserving historical farm incomes.

The empirical analysis was benchmarked against the 2000 to 2024 average net farm income of about $148,000 generated solely from crop production on a *typical farm* of approximately 1,467 acres in southwest Kansas. The typical farm size is the average of the average acreage in corn, wheat, soy, and sorghum production across southwest Kansas. Although net farm incomes and the Ogallala Aquifer were under severe pressure in the study area during this period due to extensive and intensive droughts, the study's approach shows the scalability of the income equivalence strategy to the problem. The study shows that about 0.4 acre (17,504 ft^2) of greenhouse, tomato price and yield of $2.31/pound and 15.44 pounds/ft^2, and total variable and fixed cost of $1.36/pound produced the benchmark net farm income. While tomatoes use a lot more water per acre, its production conditions in this study consumed less than one basis point (0.01%) of irrigation water currently used to produce the benchmark net farm income.

The technical results above were shown to be economically feasible results under base scenario conditions of 20 years and 8.0% discount rate. The net present value (NPV) was $706,705 and the internal rate of return was 12.9%. The payback period was under 7.4 years, and

the benefit-cost ratio was about 1.2%. The project's economic feasibility was quite robust to tomato price and yield risk, indicating that the project is not economically feasible if these two variables decrease above approximately 17% of their base value. This is equivalent to a price of $1.92 and a yield of 12.8 pounds. The Monte Carlo simulation yielded an average NPV of $635,940, a median of $607,990, and a probability of viability of 58%. The 5% Value at Risk (VaR) for the 20-year NPV is about −$4.03 million, implying less than 5% risk of discounted cumulative losses from the project exceeding $4.0 million. On the other hand, the 95% VaR for the 20-year NPV is $5.30 million. These tail analyses notwithstanding; the Monte Carlo simulations indicated a 42% probability of negative NPV versus a 58% probability of a positive NPV.

The research shows that it is economically feasible to produce an alternative crop in southwest Kansas using a novel technology that can preserve net farm incomes while saving a substantial volume of irrigation water. However, the 42% risk of loss over 20-years and base scenario parameter assumptions under the Monte Carlo simulation analysis call for implementation of downstream risk management strategies – supply management, strategic alliances, and value addition to extend shelf life – cannot be ignored if preserving farm incomes while simultaneously conserving the Ogallala is going to a viable solution in Southwest Kansas.

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Acknowledgements

"I can do all things through Christ who strengthens me." — Philippians 4:13

Above all, I express my gratitude to God. This achievement would not have been possible without His sustaining strength.

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Dedication

To God, who made a way when there was none.

To my mother Rosemene, my father Arlin, my uncle Lucien, my brother Garmoudlin, my sister Gayamah and my cousin Jupslude for your love, your prayers, and every sacrifice you made quietly so that I could reach this moment. This is for you.

Chapter 1 - Introduction

Agriculture is important to the world. It provides the primary energy that powers humanity. Agricultural land is responsible for producing approximately 90% of global food calories and 80% of proteins and fats through crops and livestock (Viana et al., 2022). In Kansas, the food and agricultural sectors directly generate $63.61 billion in statewide output (Kansas Department of Agriculture, 2025). Southwest Kansas contributes approximately $15.49 billion, representing about one-quarter of the state's total agricultural output (Kansas Department of Agriculture, 2025), making it a critical contributor to the state's agri-food economy.

The foregoing sets the stage for this research. This introductory chapter is laid out as follows. First, we provide a context of the motivating problem making this thesis relevant in today's business strategy and policy conversation in Kansas (with application to other areas in the U.S. semi-arid and arid regions). The role of the Ogallala Aquifer in underscoring the context of the research is discussed in the second section. Following that, we present the conservation initiatives that have been implemented over the years in attempts to arrest the decline of the Ogalla Aquifer, arguing that the powerful force of economics is set against these policies. Then, we provide a definition of the research problem and question, followed by the objectives. The importance of this work is then presented in order to keep it on our radar as we progress through it. Finally, the chapter ends with a brief outline of the research as presented in this thesis.

1.1 Importance of the Ogallala Aquifer to Agriculture in Southwest Kansas

Kansas is an important agricultural state. According to the Kansas Department of Agriculture (2025), agriculture contributes $63.61 billion and nearly 144,000 jobs to the Kansas economy. Recognizing the whole agri-food sector, the contribution increases to about $88 billion and approximately 261,000 jobs. The sector's contribution to the state's GDP is about 14%.

Kansas ranks first in U.S. wheat and sorghum production, and second in total cropland under production., Although called the Sunflower State, Kansas currently ranks fourth in the U.S. in sunflower production, third in cattle and calves, and sixth in irrigated cropland (Kansas Department of Agriculture, 2025). The majority of this production is in western Kansas. The 2022 USDA Census of Agriculture reports that western Kansas, defined as the Northwest, West Central, and Southwest crop reporting districts, accounts for approximately 54.4% of total Kansas agricultural sales ($13.04 billion of $23.99 billion statewide). The Southwest district alone contributes $8.55 billion, representing approximately 35.7% of statewide and approximately 65.6% of western Kansas agricultural sales (University of Kansas, 2025).

The economic vitality of southwest Kansas is largely attributed to the Ogallala Aquifer. The aquifer spans 174,000 square miles across eight states in the Great Plains: South Dakota, Nebraska, Wyoming, Colorado, Kansas, Oklahoma, New Mexico, and Texas (Silva et al., 2019; Steiner et al., 2021a) supplying about 30% of all U.S. irrigation water. It supports more than 30% of U.S. crops and livestock production (Steiner et al., 2021a) and more than $3 billion of groundwater-based production as of 2007 (García Suárez et al., 2019). In southwestern Kansas, irrigation from the Ogallala Aquifer supports a groundwater-based agricultural economy with impacts that extend beyond the farm. This system sustains one of the most productive value-added agricultural regions globally and supports employment and population across a semi-arid landscape (Aistrup et al., 2017; Steiner et al., 2021a).

Despite (or probably because of) the Ogallala Aquifer's significant contribution agricultural productivity, it is experiencing rapid and what could be irreversible depletion if the current production systems continue unabated. In extensive regions of western Kansas and the Texas High Plains, groundwater extraction for irrigation has resulted in sustained reductions in saturated thickness of approximately 1 ft/year (about 0.3 m/year) since the mid-1980s, with rates approaching twice that during droughts and local declines exceeding 80–150 ft in heavily pumped zones (Dunlap et al., 1980; McGuire, 2017). In many areas of the High Plains, annual groundwater extraction exceeds natural recharge, with extraction surpassing recharge by a factor of ten in certain locations (Anandhi et al., 2023). In the central and southern High Plains, recharge rates are often less than 0.5 in/year, whereas crop irrigation demands are roughly 1 ft/year (Anandhi et al., 2023; Gitz & Brauer, 2016; Rhodes et al., 2023). Current estimates indicate that approximately 30% of the High Plains' groundwater has already been extracted, and an additional 39% may be depleted within the next 50 years if current practices and recharge rates continue (Anandhi et al., 2023).

Irrigation constitutes between 90% and 97% of Ogallala Aquifer use in western Kansas and studies consistently indicate that if current management practices persist, substantial areas of the aquifer will no longer support economically viable irrigation within the next several decades (Aistrup et al., 2017; Baumhardt et al., 2024; Gibson & Gray, 2016; Steward et al., 2013a). Projections for southwest Kansas suggest that, if current groundwater extraction rates persist, water levels in many communities will decline to levels insufficient to support irrigated agriculture less than 25 years, even under average climate conditions (Nozari et al., 2022; Steward et al., 2013a). Without irrigation, both models and evidence from other regions of the High Plains indicate sustained declines in agricultural productivity, reductions in gross farm revenue and value added, and contractions in employment and local business activity (Deines et al., 2020; Terrell, 2002). It has also been estimated that about a quarter of currently irrigated land may transition away from irrigation by 2100 to lower-value pasture, resulting in greater income losses and reduced economic multipliers (Deines et al., 2020).

1.2 Conservation Strategies and Their Limitations

Over the past three decades, major Ogallala stakeholders, including farmers, water managers, and policymakers in western Kansas, have implemented innovation and significant conservation strategies in attempts to address the aquifer's depletion problem. Farmers have increasingly adopted technologies and practices that enhance the timing and placement of water, such as energy-efficient precision and subsurface drip irrigation, variable rate pivots, soil moisture monitoring, and irrigation scheduling targeting the crop growth stages most sensitive to yield (Deines et al., 2019a, 2021; Steiner et al., 2021a). These changes are frequently implemented alongside broader system-level adjustments. Examples include transitioning from corn to less water-intensive crops such as sorghum and wheat, adopting deficit and growth stage irrigation strategies, and incorporating conservation tillage, residue retention, diversified crop rotations, and additional soil health practices to enhance infiltration and water use efficiency under limited irrigation conditions (Cano et al., 2018; Chen et al., 2018; Nilahyane et al., 2023; Steiner et al., 2021a).

Kansas has progressively expanded the authority and flexibility of its groundwater governance framework. This approach empowers locally controlled Groundwater Management Districts (GMD) to implement mechanisms such as Local Enhanced Management Areas (LEMAs), Water Conservation Areas, and multi-year allocation schemes that impose enforceable pumping caps while permitting carryover, intra-farm water right flexibility, and, in certain cases, trading among users (Deines et al., 2019a; Perez-Quesada & Hendricks, 2021a; Sophocleous, 2012; Steiner et al., 2021a). Evaluations of the Sheridan-6 (SD-6) Local Enhanced Management Area (LEMA), for example, indicate that this irrigator-driven, state-supported model reduced groundwater pumping by between 25% and 31% during its first five years while irrigated area and net farm income were largely maintained, with many participants surpassing their conservation targets and initial evidence suggesting stabilization of groundwater levels (Castaño-Sánchez et al., 2025; Deines et al., 2021; Steiner et al., 2021a).

While these initiatives have not fully halted regional decline in the Aquifer, they illustrate that coordinated technological, administrative, and policy innovations can significantly slow resource depletion and serve as a model for implementing stricter, locally legitimized conservation measures in the High Plains and other water-stressed aquifer systems (Deines et al., 2019a, 2021; Steiner et al., 2021a; Wagner, 2017). However, the forecast from the majority of hydrologists watching the Ogallala seem to suggest that in the big scheme of arresting the problem, something different needs to happen if the competition for water is not going to lead to more difficult challenges (Shoko, 2025)

1.3 Innovation in Agricultural Production System

The gap between the magnitude of the Ogallala depletion problem and the limited impact of existing conservation strategies clearly points to the need for structural innovation in agriculture in southwestern Kansas. The relevant question is no longer simply how to use water more efficiently within current production systems, but rather whether fundamentally different production systems can be technically, operationally, and economically viable to radically reduce the volume of groundwater needed per dollar of farm income generated.

Controlled environment agriculture (CEA), particularly hydroponic greenhouse production, has become a prominent global strategy for intensifying food production while reducing pressure on to land and water resources in arid and water-constrained regions. CEA systems enable precise regulation of temperature, humidity, light, and nutrient delivery. This method protects crops from heat, drought, and soil degradation, which increasingly constrain open-field agriculture, and supports year-round production with significantly higher yields per unit area compared to conventional systems (Farvardin et al., 2024; Niu & Masabni, 2018a; Pomoni et al., 2023). Across a wide range of horticultural crops, hydroponic systems typically reduce irrigation water consumption by 70% to 95% compared to soil-based cultivation, with recirculating designs achieving reductions of approximately 90% or more, while maintaining or increasing yields (Campbell et al., 2005; Pomoni et al., 2023; Regmi et al., 2024a; Singh et al., 2024; Sirhan et al., 2025). Comparative studies report water demands for lettuce on the order of 20 L/kg/y in hydroponics versus roughly 250 L/kg/y in conventional fields, alongside 3.5- to 11-fold increases in yield per square meter in greenhouse and vertical hydroponic setups (Farvardin et al., 2024; Hasan et al., 2026; Pomoni et al., 2023). These productivity and efficiency gainshave contributed to a rapid growth in the commercialization of hydroponics production technologies. The global market is now valued in the billions of dollars and continues to expand as firms and growers adopt soilless systems in urban centers, deserts, and other regions with limited arable land (Amarasinghe et al., 2025a; Rajendran et al., 2024; Sirhan et al., 2025).

Whitin the context of shifting toward water-efficient, high-value horticulture, greenhouse tomato production emerges as a particularly promising candidate for evaluation in southwest Kansas. Tomatoes are among the world’s most important vegetable crops by volume and economic value, with global annual production exceeding 100 million tons and an estimated farm-gate value in the tens of billions of dollars, reflecting their central role in both fresh and processed markets (Verdoliva et al., 2021a). High-tech greenhouse tomato systems employ climate-controlled environments and carbon dioxide fertilization to achieve high yields, reaching

60.2 to 71.6 kg m^{-2} per cycle or more (Maureira et al., 2022a). Closed hydroponic systems further enhance efficiency by recycling nutrient solutions, reducing water consumption by up to 96% and fertilizer usage by 97% compared to open systems (Fayezizadeh et al., 2021). Economic analyses from Greece, Egypt, Pakistan, and other water-limited regions demonstrate that commercial hydroponic tomato greenhouses can be profitable investments over a 5- to 10-year period (Abdelmawgoud et al., 2021; Michalis et al., 2023a; Sardar et al., 2024). These studies show positive net present values, favorable internal rates of return, and profits several times higher than those of soil-based systems, despite higher initial capital costs. The increased profitability is primarily attributed to higher yields and more efficient resource utilization.

In addition to water conservation, the proposed enterprise shift is supported by a strong market rationale based on the structural transformation of the U.S. fresh tomato supply chain. Since 2000, U.S. fresh tomato import volumes have increased by 176 percent, with the bulk originating from Mexico where greenhouse tomato production has significantly expanded (Weber & Davis, 2024). In 2023, total U.S. fresh tomato market was valued at $3.28 billion, with $2.82 billion accounted for by Mexico (World Bank WITS, 2023). Imports represented an estimated 88 percent of the domestic greenhouse tomato supply in 2023 (Weber & Davis, 2024). Meanwhile, U.S. domestic tomato producers have struggled to compete, supplying less than one-third of national fresh tomato demand (Cui et al., 2022).

Producing greenhouse tomatoes in southwest Kansas, a region not currently known for vegetable production, could contribute to addressing this domestic production gap. The study uses an income-equivalence framework as the bedrock of its option selection. That is, any solution to reduce water use in agriculture must result in the same income level or higher under the prevailing production system. In other words, farm income and livelihood should not be sacrificed for water conservation. It is a radical approach to the water conservation (and other resource conservation) solutions, recognizing that water and other resources are, for the farmer, inputs to generate income for making a living.

1.4 Research Question

The depletion of the Ogallala Aquifer, the limitations of existing conservation strategies, and the opportunities presented by controlled environment agriculture collectively motivate the central research questions of this thesis:

> How technically, operationally, and economically feasible is greenhouse tomato production, as an alternative novel enterprise, in contributing to addressing the current water challenges in western Kansas while maintaining or enhancing farmers' incomes?

This question is informed by a key insight that distinguishes this research from previous aquifer conservation studies. Rather than focusing on reducing water use within existing production systems, this study investigates whether adopting an entirely new production system can simultaneously address water conservation while securing agricultural livelihoods. The selection of tomatoes as the focal alternative enterprise is both intentional and analytically justified. Although tomatoes are typically water-intensive in field production, which would generally preclude their consideration in water-scarce regions, hydroponic greenhouse systems enable exceptionally high water productivity to be achieved. The central insight is that water conservation at both farm and regional levels can be achieved not by increasing output per unit of water, but by substantially reducing the total acreage and, consequently, the total water volume required to generate equivalent farm income.

1.5 Research Objectives

The nature of the research question implies that this thesis is rooted in simulation techniques. It constructs a "typical farmer" for whom the performance of the alternative production is conducted in comparison to their traditional crop production. Based on this understanding, the overall objective of this research is to identify the conditions under which the historical average net farm income in the study area can be maintained under an alternative crop production enterprise while reducing irrigation water use. The specific objectives are as follows:

1. Develop the comparative "typical farmer" characteristics to provide the base reference for conducting the comparison of the research solution against the status quo.
2. Build the capital and operational expenditure structures for the new enterprise (greenhouse) solution in order to analyze the complete financial implications of any shift to the new enterprise.
3. Simulate the technical, operational, and economic feasibility of the new enterprise solution under alternative critical variable assumptions in order to assess the potential riskiness of the solution in sustaining farm net incomes.
4. Estimate the relative change in water use resulting from the economically feasible net income conserving solution developed by the research.

1.6 Principal Contribution of the Thesis

Achieving the objectives outlined in this thesis is expected to contribute significantly to addressing the water crisis and to encourage researchers and policymakers to reconsider how problems are defined and solved. The principal innovation of this research lies in redefining the problem as one of net income security rather than focusing exclusively on water conservation.

This reframing is significant because it emphasizes the human dimension and the economic realities encountered by water resource managers.

Framing the problem as net income security challenges the conventional competitive market perspective, which maintains that production should continue as long as price exceeds marginal cost. This perspective treats the farmer as an abstract profit-maximizing agent whose behavior is fully explained by input and output prices. However, such a framing is insufficient. For the typical farm operator in western Kansas, the purpose of farming is not simply to satisfy a marginal cost condition; rather, it is to secure a net income that sustains a defined way of life and standard of living for the farm family. Incorporating this view of the farmer into the analysis introduces non-pecuniary values into the definition of net income. The production motivation for the decision-maker is not only pecuniary returns, but the livelihood security and lifestyle continuity that a particular income stream enables.

The foregoing distinction has direct implications for how the price-greater-than-marginal-cost condition operates in practice. For this economic agent, the perceived value of production includes more than the market price of the commodity, and the perceived cost is more than purchased inputs and capital charges. The analysis presented here suggests that, having organized economic life around a certain net income and an expected income growth rate, the farm decision maker will exhaust available alternatives before abandoning that standard. This behavioral logic underpins the enterprise substitution analysis central to this thesis. Identifying an alternative that can match the income security of the current system while substantially reducing aquifer withdrawals is not merely a technical exercise; it directly responds to the way farm families in southwest Kansas experience and define the problem.

1.7 Thesis Outline

The remainder of this thesis is organized as follows. Chapter 2 provides the literature review and conceptual framework for the study. It examines scholarly research on Ogallala Aquifer depletion and its agricultural and socioeconomic consequences, reviews the economics of controlled environment agriculture and greenhouse tomato production, and situates the study within the broader literature on farm-level technology adoption and agricultural adaptation under resource constraints.

Chapter 3 describes the data and analytical methods employed in the study. It outlines the development of the Typical Farmer baseline, the enterprise budget model for greenhouse tomato production, the discounted cash flow and Monte Carlo simulation frameworks, and the water productivity measures used to assess aquifer-level impacts.

Chapter 4 presents and discusses the results of the empirical analysis. The findings are organized according to four secondary objectives: baseline farm income and water use, greenhouse enterprise economics under baseline assumptions, economic feasibility under uncertainty and sensitivity analysis, and comparative water productivity outcomes.

Chapter 5 concludes the thesis. It summarizes the principal findings in relation to the research questions, draws conclusions regarding the technical, operational, and economic feasibility of greenhouse tomato production as an adaptation strategy in southwest Kansas, and discusses the policy implications for aquifer management, agricultural development, and rural economic planning in the region. Recommendations for future research and industry strategic directions are also presented. A complete list of references follows Chapter 5, and supplementary materials including detailed budget tables, simulation inputs, and sensitivity analysis outputs are provided in the appendices.

Chapter 2 - Literature Review

The ensuing literature review shows a substantial body of research across the thematic areas relevant to this thesis. The areas encompass the Ogallala Aquifer's depletion dynamics, conservation strategy effectiveness, controlled environment agriculture (CEA) and greenhouse tomato agronomy and economics, and agricultural investment analysis. However, several gaps remain that the present study aims to address. This thesis contributes to the Ogallala Aquifer conservation literature by shifting the focus from volumetric water reduction to an income equivalence framework, demonstrating that enterprise diversification can achieve conservation objectives without compromising producer profitability. By conducting an economic feasibility analysis of greenhouse tomato production in southwest Kansas, the thesis addresses a significant gap in local crop diversification strategies. Methodologically, the research enhances agricultural investment appraisal by combining discounted cash flow analysis with Monte Carlo simulations using standard deviation, providing robust probability distributions for net present value, internal rate of return, and payback periods that more accurately reflect the price and yield risks associated with high-value specialty crops.

2.1 Dependance of Southwest Kansas on Groundwater

The agricultural economy of southwest Kansas operates as a highly productive, hyper-extractive system and functions as a crucial value-added hub for the U.S Great Plains, sustained primarily by intensive withdrawals from the Ogallala Aquifer (Aistrup et al., 2017; Steiner et al., 2021a). Following a rapid expansion of groundwater extraction between the 1950s and 1970s, driven by the widespread adoption of center-pivot irrigation technology, the landscape transitioned from semi-arid grassland to a major producer of irrigated corn, sorghum, wheat, and alfalfa (Aistrup et al., 2017; Steiner et al., 2021a). This system of crop production facilitated the growth of concentrated animal feeding operations that supply some of the world's largest meatpacking plants (Aistrup et al., 2017; Steiner et al., 2021a) and ethanol energy plants resulting in an increase in employment and substantial economic growth in the region (Steiner et al., 2021a). Even though these positives impact have been observed, the region now faces the long-term consequences of severe groundwater depletion and an increasingly arid climate, both of which threaten the future viability of its water-dependent economy (Aistrup et al., 2017; Steiner et al., 2021a).

2.1.1 Economic Impact of Southwest Kansas Irrigated Agriculture

Irrigated agriculture contributes over $500 million in additional annual state-level revenue compared to dryland alternatives (Lamb et al., 2021; Steward et al., 2013b), a figure reported in nominal dollars that, if adjusted to 2026 terms, would be meaningfully higher given cumulative inflation over the intervening period. Maize serves as the principal economic driver, yielding a median gross profit of approximately $530 per hectare under full irrigation (Araya et al., 2019). However, this economic model faces a significant sustainability crisis. Approximately 30% of the aquifer has already been depleted, and an additional 39% is projected to be lost within the next 50 years if current pumping trends continue (Lamb et al., 2021; Steward et al., 2013b). This depletion creates a pronounced tension between immediate profitability and long-term socio-economic stability. Because natural recharge supplies only about 15% of current extraction rates, full recovery of the aquifer could require 500 to 1,300 years (Steward et al., 2013b). The ongoing decline is expected to affect utility rates, industrial stability, and local public finances, potentially resulting in a fiscal and social crisis that could undermine municipal infrastructure and manufacturing chain (Deines et al., 2019b; Lamb et al., 2021; Xiang et al., 2025). Even with aggressive management, resources such as the High Plains Aquifer can be conserved but not fully sustained (Xiang et al., 2025). To address these challenges, research recommends a strategic shift toward water-efficient "rescue crops" such as winter wheat and grain sorghum, which maintain median returns of $252 and $180 per hectare, respectively, even under rainfed conditions (Araya et al., 2019). Failure to implement adaptive strategies, including the adoption of more resilient crops or the upgrade to subsurface drip irrigation, could lead to a decline in groundwater saturated thickness of 20% to 55% by 2050 (Xiang et al., 2025). The region's future depends on balancing the short-term benefits of intensive irrigation with the long-term necessity of resource preservation. Achieving sustained food security and regional stability requires a fundamental institutional transformation. Resource management should progress beyond depletion toward integrated allocation of land, crops, and water. Implementing regulatory frameworks that prioritize both the health of natural capital and economic productivity enables a transition from resource exhaustion to resilient adaptation (Araya et al., 2019; Steward et al., 2013b; Xiang et al., 2025).

2.2 Conservation Strategies

2.2.1 Farm-Level Technological Responses in The High Plains

Technological and management transitions in the Texas High Plains increasingly focus on mitigating depletion of the southern Ogallala Aquifer by improving water use efficiency, rather than discontinuing irrigated production (Fan et al., 2022; Himanshu et al., 2021). This transition emphasizes the adoption of advanced irrigation systems, particularly Subsurface Drip Irrigation (SDI) and Low-Energy Precision Application (LEPA), which replace conventional furrow or older spray methods (Himanshu et al., 2021; Mitchell-McCallister et al., 2020; Reynolds et al., 2020). SDI is noted for achieving the highest absolute yields and increasing water use efficiency by up to 147% through the elimination of surface evaporative losses. In contrast, LEPA remains a viable and risk-efficient alternative due to its lower capital investment and reliable performance under varying water availability (Fan et al., 2022; Mitchell-McCallister et al., 2020; Reynolds et al., 2020). The integration of these technologies allows producers to implement Growth-Stage-Based Deficit (GSBD) irrigation strategies, which prioritize water application during critical physiological stages such as peak bloom and reduce irrigation during less sensitive periods (Himanshu et al., 2021; Mitchell-McCallister et al., 2020). Economic analyses indicate that these precision management strategies enable producers to sustain profitability and maximize net returns, even when groundwater extraction is restricted to 75% of full crop requirements (Fan et al., 2022; Reynolds et al., 2020). The adoption of SDI and LEPA, together with optimized crop-water allocation, constitutes a primary strategy for safeguarding the regional agricultural economy and fostering long-term resilience in the face of declining well capacities (Mitchell-McCallister et al., 2020; Reynolds et al., 2020).

The integration of advanced hydro-agronomic modeling with regional management strategies establishes a robust framework for addressing the rapid depletion of the High Plains (Ogallala) Aquifer in Southwest Kansas. Research in Finney County indicates that adopting high-efficiency irrigation technologies, particularly subsurface drip irrigation (SDI) in conjunction with reduced land-crop-water allocation, may extend the aquifer's lifespan (Xiang et al., 2025). These targeted management practices have demonstrated substantial water conservation potential, with simulations showing that up to 28.8 meters of groundwater can be preserved in maize-dominated scenarios (Xiang et al., 2025). Additionally, studies from neighboring areas of the High Plains emphasize the importance of optimizing irrigation depths and crop selection to minimize seasonal water use while maintaining yields for key crops such as corn and sorghum (Chen et al., 2021). In addition to technological advancements, strategic modifications in agronomic practices, including adjusted planting schedules and crop diversification, are crucial for sustainable resource management in Finney County and the broader Southwest Kansas region. Evidence indicates that late planting of corn and prioritizing early planting of winter wheat can significantly contribute to water conservation while sustaining agricultural productivity (Chen et al., 2021). Moreover, shifting from water-intensive maize to more resilient, drought-tolerant crops such as sorghum and winter wheat is recognized as an effective approach to mitigating groundwater depletion (Xiang et al., 2025). Triticale may also be considered as a forage-oriented alternative in southwest Kansas due to its relative drought tolerance, reduced water requirements compared to more water-intensive crops, and its potential value within integrated crop-livestock systems. Nevertheless, these integrated strategies underscore a critical limitation: although aggressive conservation measures and revised planting schedules can extend groundwater availability, they are unlikely to fully counteract the effects of climate change or achieve complete aquifer stabilization (Chen et al., 2021; Xiang et al., 2025). Therefore, these management adaptations should be viewed as essential for prolonging resource availability rather than as definitive solutions for groundwater sustainability in increasingly arid environments (Chen et al., 2021; Xiang et al., 2025).

Recent literature indicates that although farm-level technological adaptation is essential for groundwater management, it is insufficient to address the Ogallala depletion problem without robust institutional mechanisms (Scanlon et al., 2021). Data-driven evaluations of the Sheridan-6 (SD-6) Local Enhanced Management Area (LEMA) reveal that isolated improvements in irrigation delivery frequently result in a rebound effect, or Jevons paradox, where efficiency gains are redirected to expand irrigated acreage or cultivate more water-intensive crops (Scanlon et al., 2021; Whittemore et al., 2023). In the Central and Southern High Plains, where groundwater extraction can surpass recharge rates by a factor of ten, the adoption of high-efficiency systems has not halted depletion in the absence of enforceable regulatory constraints and pumping caps (Scanlon et al., 2021; Whittemore et al., 2023). The SD-6 LEMA demonstrated that removing "use it or lose it" regulatory barriers and implementing multi-year allocations enabled efficiency improvements to yield a 27.4% to 31% reduction in total groundwater use (Steiner et al., 2021b; Whittemore et al., 2023).

2.2.2 Institutional and Governance Responses: LEMAs and Groundwater Management

The institutional response to the depletion of the High Plains aquifer in Kansas has shifted toward locally driven, state-supported groundwater governance, with the Local Enhanced Management Area (LEMA) framework serving as a central component. While the Water Appropriation Act continues to provide the foundational legal structure for the state's prior-appropriation system, the 2012 LEMA legislation represented a significant change by authorizing Groundwater Management Districts (GMDs) to propose mandatory, community-scale pumping reductions in designated high-priority areas (Steiner et al., 2021b). These geographically defined programs allow irrigators, GMD boards, and the Chief Engineer of the Kansas Department of Agriculture to collaboratively design enforceable multi-year pumping allocations, thereby offering producers flexible water budgets (Steiner et al., 2021b; Whittemore et al., 2023). The effectiveness of this governance framework is exemplified by the Sheridan-6 (SD-6) LEMA in northwest Kansas. Between 2013 and 2021, the SD-6 LEMA achieved a reduction in groundwater pumping estimated at 26% to 31% compared to business-as-usual scenarios (Deines et al., 2019b; Steiner et al., 2021b). Transitioning from a "use it or lose it" approach to a system that prioritizes net profit over raw yield enabled substantial conservation without reducing net farm income. The LEMA nearly halted water-level declines in the area, slowing the rate from -0.49 meters per year to -0.04 meters per year, which demonstrates that agricultural productivity can be maintained while achieving significant aquifer stabilization (Deines et al., 2019b; Whittemore et al., 2023).

To complement the mandatory LEMA model, Kansas introduced Water Conservation Areas (WCAs) in 2015, offering a more flexible avenue for individual or small-group participation (Perez-Quesada & Hendricks, 2021b; Whittemore et al., 2023). Unlike the LEMA, which mandates compliance for all users within a boundary, the WCA model allows for purely voluntary participation among water right holders without requiring GMD board intervention. In Wichita County, the strategic reduction of irrigated acreage through WCA and LEMA participation led to a 38.5% drop in total usage (Whittemore et al., 2023). However, research suggests that voluntary frameworks can struggle with "free-rider" problems, often resulting in lower enrollment and total water reduction than their mandatory counterparts (Perez-Quesada & Hendricks, 2021b). The effectiveness of these governance instruments is reinforced by Kansas's comprehensive regulatory and data infrastructure. With 98% of wells equipped with totalizing flowmeters, the Chief Engineer possesses the monitoring capacity necessary to transform local initiatives into enforceable regulatory measures (Steiner et al., 2021b; Whittemore et al., 2023). Yet, these policies fail to address the farmers' needs to generate incomes from the deployment of the water. Alternative solutions are needed if the water and income challenges are going to be addressed.

2.3 Controlled Environment Agriculture and Greenhouse Tomato Production

Research on controlled environment agriculture (CEA) and greenhouse tomato production covers plant science, engineering, and economics. Recent studies primarily examine their water-saving potential and yield improvements relative to conventional agriculture. Additionally, the literature details the operation of commercial hydroponic systems and evaluates the profitability of greenhouses across various regions. CEA technologies shows significant variation, from basic high tunnels to advanced vertical farms and automated greenhouses. Through precise control of climate, light, and nutrient delivery, these systems facilitate consistent yields and enhanced crop quality independent of external weather conditions. Greenhouse tomato production, which constitutes a substantial segment of the industry, demonstrates the potential of soilless cultivation. However, concerns remain regarding the high energy requirements and long-term economic sustainability of these operations.

2.3.1 Controlled Environment Agriculture: Overview and Water Efficiency

Controlled environment agriculture (CEA) includes a range of protected and indoor production systems, extending from basic shade structures and hoop houses to fully enclosed, multi-layer crop production facilities and vertical farms. All CEA systems possess the ability to actively monitor and regulate key microclimate variables, such as temperature, humidity, light intensity and spectrum, CO_2 concentration, and water-nutrient delivery, within engineered structures including greenhouses and plant factories (Niu & Masabni, 2018b; Ramin Shamshiri et al., 2018). By separating crop production from external weather conditions, CEA facilitates year-round cultivation, precise pest and disease management, and consistent yields despite climate variability and land degradation (Cowan et al., 2022; Niu & Masabni, 2018b; Ramin

Shamshiri et al., 2018). Modern CEA incorporates sensors, automation, and Internet of Things (IoT) control systems to maintain optimal growing conditions and enable precise input management. Such technological integration increases the viability of CEA for urban and peri-urban food production, especially in regions characterized by limited land resources and heightened climatic risks (Dsouza et al., 2023; Ramin Shamshiri et al., 2018; Vatistas et al., 2022). Since crops are cultivated in inert substrates or hydroponic solutions instead of soil, CEA can be implemented on non-arable, contaminated, or urban land, thereby broadening the geographic scope for intensive food production (Cowan et al., 2022; Vatistas et al., 2022).

Water management is a key advantage of CEA relative to open-field agriculture. Enclosing the crop environment reduces evapotranspiration. Furthermore, precision irrigation and closed-loop recirculation facilitate the reuse of water and nutrients, thereby minimizing losses to runoff and deep percolation (Cowan et al., 2022; Vatistas et al., 2022). Reviews of hydroponic CEA consistently indicate that water use can be reduced by over 90% compared to conventional soil-based systems, with fertilizer savings of approximately 60%, depending on crop type and system configuration (Amarasinghe et al., 2025b; Regmi et al., 2024b). In hydroponic greenhouses and vertical farms, technologies such as nutrient film techniques (NFT), deep-water culture (DWC), aeroponics, and recirculating drip systems enable precise metering of nutrient solutions and effective recovery of drainage. These approaches significantly increase water use efficiency (WUE) per unit of biomass (Majid et al., 2021; Regmi et al., 2024b; Vatistas et al., 2022; Verdoliva et al., 2021b).

According to Verdoliva et al. (2021), CEA comparisons show that hydroponic tomatoes in DWC or drip systems transpire less water yet maintain similar yields to soil-grown plants, resulting in substantially lower product water use and improved WUE without compromising sugar content or total soluble solids. These systems also reduce crop duration and achieve substantial water savings compared to soil-based cultivation. Specifically, NFT systems can reduce irrigation demand by approximately 60 to 70 percent relative to protected soil systems (ÇekiN et al., 2024; Majid et al., 2021). System-level assessments of CEA suggest that, under optimal conditions, only fractions of a liter of water to grow a kilogram of food, compared with thousands of liters per kilogram in field production, making water-efficient CEA particularly attractive for arid and water-scarce regions (Calvo-Baltanás et al., 2025; Cowan et al., 2022). In lettuce production, for example, DWC and NFT systems within controlled environments result in significantly higher yields and improved quality.

2.3.2 Greenhouse Tomato Production

Tomato (*Solanum lycopersicum L.*) is one of the world's most widely grown crop, accounting for 12.3% of the total global vegetable output and exceeding an estimated 180 million tons annually. In addition to its economic significance, tomato is also valued for its nutritional content, processing versatility, and playing central role in both fresh and processed markets (Liu et al., 2025; Maurya et al., 2025). Rising demand, combined with increasing climatic vicissitudes, and soil degradation in major production regions, is causing a structural transition from open-field cultivation to protected and greenhouse systems. These systems protect crops against weather extremes, pests, and diseases, while enhancing resource use efficiency (Koukounaras, 2020; Liu et al., 2025; Maurya et al., 2025). In countries such as China and India, greenhouse and solar-greenhouse tomatoes are now central to urban "vegetable basket" and to smallholder income diversification, especially where open-field productivity is constrained by heat, drought, or disease pressure (Liu et al., 2025). Simulation studies and empirical case studies conducted in North America and Europe indicate that high-tech greenhouses can yield approximately six to 10 times more tomatoes compared to traditional field cultivation, particularly when utilizing hydroponic and/or aeroponic conditions under year-round cropping (Maureira et al., 2022b; Zhou et al., 2021). In Washington State, a modeled high-tech greenhouse production resulted in yields that were 6.4 times higher than those of open-field systems; however, this approach required substantially greater energy inputs and produced higher greenhouse gas emissions per kilogram of fruit (Maureira et al., 2022b). Similar patterns emerge from sustainability assessments in Mexico and Europe, where commercial greenhouse yields typically exceed 180–283 tons/ha/yr, with the highest-technology operations surpassing these benchmarks (Suazo-López et al., 2024; Zhou et al., 2021).

In greenhouse horticulture, tomato frequently serves as the primary crop for soilless systems, which separate production from soil limitations and allow for precise management of root-zone conditions. Often called high-tech closed-loop hydroponic greenhouses in Europe and North America, these greenhouses typically utilize rockwool or coir substrates, automated fertigation, and continuous environmental monitoring to optimize nutrient and water utilization (Appolloni et al., 2021; D'Amico et al., 2023; Koukounaras, 2020). Comparative analyses show that such systems can substantially reduce water and fertilizer inputs per kilogram of fruit relative to soil-based cultivation, while maintaining or increasing yields (Koukounaras, 2020; Maureira et al., 2022b; Zhou et al., 2021). Modern commercial greenhouse tomato production increases yields by incorporating CO_2 enrichment which can raise yields by about 30% (Nomura et al., 2024), and supplemental LED lighting, which increases average yields by 40% (Appolloni et al., 2021, 2023).

2.3.3 The Competitive Landscape of the U.S. Tomato Market

The U.S. fresh tomato market has undergone substantial structural transformation, driven by the contraction of the domestic open-field industry, the growth of the greenhouse sector, and a significant rise in imported supply (Cui et al., 2022). Whereas domestic production previously satisfied most national demand, by 2021, U.S. growers supplied only one-third of total fresh tomato volume, representing a 50% reduction in market share over the past two decades (Cui et al., 2022). Total production declined from 3.9 billion pounds in 2000 to 2.7 billion pounds in 2015 (Guan et al., 2018). Specifically, open-field output fell from 1.89 million metric tons to 0.97 million metric tons during this period (Cui et al., 2022).

Several factors have contributed to the decline in domestic production, including significant yield losses in states such as Florida following the federal ban on the fumigant methyl bromide which contributed to a loss cost and price competitiveness (Guan et al., 2018). With demand increasing, the U.S. has increasingly relied on imports to compensate for declining domestic output. Imports rose from 1.1 billion pounds in 2000 to 3.2 billion pounds by 2016 (Guan et al., 2018). These imports are primarily from Mexico (Cui et al., 2022; Guan et al., 2018).

The intensification of trade following the implementation of NAFTA has been singled out as a primary driver of the domestic challenges of the U.S. field tomato industry. For example, tomato imports from Mexico increased by 424% in volumes in 2019 (Chanda et al., 2021; S. Li et al., 2022). This development has led many industry stakeholders to characterize the current trade environment as "one-sided" (Chanda et al., 2021). Domestic producers report facing significant challenges competing with Mexican imports, which they note benefit from substantially lower labor costs and extensive government subsidies for protected agriculture

(Chanda et al., 2021). However, it would seem that Mexico has shifted more rapidly toward greenhouse production while growing varieties aligned with evolving U.S. consumer preferences, such as tomatoes-on-the-vine (TOV) and snacking tomatoes. The adoption of CEA production has also given Mexican producers a competitive advantage over their U.S. counterparts with respect to yield improvements and pricing. U.S. growers also report experiencing considerable regulatory and environmental obstacles, further limiting their ability to compete (Cui et al., 2022). For example, the mandated phase-out of methyl bromide caused yield losses of up to 20% in Florida's traditional open-field systems (Cui et al., 2022). However, its severe ozone depleting properties brought it into focus under the Montreal Protocol, increasing costs and lowering yield without any effective substitute soil fumigant (Cao et al., 2019; Osteen, 2003).

The consequent effect of increasing imports resulting from declining domestic production and undiminished demand have produced an opportunity in the domestic market that is worth exploring. Currently, domestic tomato producers are often compelled to abandon crops when market prices fall below harvesting costs or when they are sorely uncompetitive against imports (Chanda et al., 2021; S. Li et al., 2022). The search for competitive advantage has driven significant industry consolidation in search of scale economies. For example, the number of active tomato growers in Florida has decreased from 300 to only 25 after the implementation of NAFTA (Chanda et al., 2021). Within this competitive environment greenhouse production has become both a disruptive force and a strategic opportunity in the evolving U.S. tomato market, now representing approximately one-third to two-fifths of retail fresh tomato volume (Cook & Calvin, 2005; Cui et al., 2022). This transformation is primarily driven by increasing consumer demand for specialty formats such as grape, cherry, and tomatoes-on-the-vine (TOV), which are better suited for protected cultivation than traditional field-grown varieties to meet consumer expectations for consistency, allowing them to command premium prices ranging from $0.99/lb to over $3.99/lb (Simonne et al., 2006).

2.3.4 Economic Feasibility of Greenhouse Tomato Production

The economic feasibility of global commercial greenhouse tomato production depends on the effective integration of high yield performance, stringent cost control, and strategic market positioning. Economic feasibility analyses have been conducted across various geographic and economic contexts. In regions such as the Mediterranean basin, Southeastern Europe, high-latitude areas like Norway, and emerging markets in East and South Asia, research consistently identifies protected cultivation as both capital and energy intensive (Baytorun & Zaimoğlu, 2023; Min et al., 2022). Despite these substantial entry barriers and operational costs, protected systems can generate higher net returns per unit area than traditional open-field or unheated methods (Ostojić et al., 2024; Sagar & Singh, 2023). For example, advanced soilless systems in the Mediterranean can achieve yields exceeding 30 kg/m^2, significantly increasing the proportion of first-quality produce (Baytorun & Zaimoğlu, 2023). In the Tarai region of India, the adoption of polyhouse systems is supported by notable increases in seasonal income, contingent upon effective water management and optimized initial capital investments (Sagar & Singh, 2023).

The adoption of advanced greenhouse systems introduces considerable financial challenges, particularly in relation to fluctuating energy prices and agricultural labor availability. In Northern Europe, the profitability of year-round production in high-latitude climates such as Norway relies on the implementation of energy-saving technologies, including LED lighting, heat pumps, and thermal screens (Naseer et al., 2022). These technical efficiencies are essential, as even seasonal cultivation in these regions requires careful management of heating needs and market pricing to ensure positive net financial returns (Naseer et al., 2021). In East Asian glasshouse operations, commercial risk is underscored by significant variations in net present values, which are influenced by regional climate and seasonal price volatility. This indicates that high-technology investments in this industry are inherently risky due to elevated energy consumption (Min et al., 2022).

The sustainability of CEA tomato systems depends on their capacity to withstand market volatility and be profitable. In Western Greece, hydroponic greenhouse models can achieve full capital recovery within five years, although their feasibility is sensitive to fluctuations in input costs and producer prices (Michalis et al., 2023b). Similar economic potential is observed in regions such as Vojvodina, where organic greenhouse models demonstrate greater resilience to price fluctuations than open-field systems, especially when intercropping is employed (ÇekiN et al., 2024). Collectively, these global case studies indicate that, although protected tomato systems require intensive resource management, they provide a viable means of increasing local food production and achieving higher profitability when technical and market conditions are favorable (Michalis et al., 2023b; Naseer et al., 2021).

Researchers assess the economic feasibility of protected cultivation using standard investment metrics such as Net Present Value (NPV), Internal Rate of Return (IRR), and payback period (Michalis et al., 2023b; Min et al., 2022). Given the capital-intensive nature of these systems, evaluations often include detailed lifecycle cost frameworks and stochastic modeling, such as Monte Carlo simulations, to address the sector's inherent economic uncertainties (Min et al., 2022; Naseer et al., 2022). These analyses consistently identify three primary determinants of commercial success. First, projects must achieve high yields relative to initial capital investment to ensure viability (Naseer et al., 2021; Peña et al., 2022). Second, profitability is highly sensitive to market conditions; thus, capturing price premiums through seasonality or product quality is essential to mitigate producer price volatility (Michalis et al., 2023b; Min et al., 2022). Third, effective management of energy costs is crucial, as heating and natural gas expenses often match or surpass labor as the dominant variable cost in advanced greenhouse systems (Naseer et al., 2021, 2022). The integration of sensitivity analysis of alternative scenarios with qualitative assessments such as SWOT analysis enables a comprehensive assessment of how regional climate and market conditions influence the feasibility of various technological packages (Michalis et al., 2023b; Peña et al., 2022).

2.4 Gaps in the Literature

The forgoing literature review shows a substantial body of research across the thematic areas relevant to this thesis: Ogallala depletion dynamics, conservation strategy effectiveness, CEA, and greenhouse tomato agronomy and economics, and agricultural investment analysis. However, several gaps remain in the literature, some of which the present study aims to address. The most critical contribution to the literature is shifting the focus of the conservation of the Ogallala Aquifer from volumetric water reduction to an income equivalence framework. The essence of this framework is demonstrating that enterprise diversification can achieve conservation objectives without compromising producer income levels. By assessing the economic feasibility of greenhouse tomato production in southwest Kansas, the thesis contributes to addressing a significant gap in local crop diversification strategies. Methodologically, the research enhances agricultural investment appraisal by combining discounted cash flow analysis with Monte Carlo simulations, providing robust probability distributions for net present value, internal rate of return, and payback periods that more accurately reflect the price and yield risks associated with high-value specialty crops.

Chapter 3 - Data and Methods

This chapter describes the data sources, model structure, and analytical procedures employed to assess the economic feasibility of a hypothetical high-technology hydroponic greenhouse tomato enterprise as an alternative production system for representative traditional farm operations in southwest Kansas. Rather than imposing an arbitrary facility size, the analysis begins from an income-equivalence criterion: the greenhouse footprint is determined endogenously as the production area required to generate the annual net farm income earned by the typical farmer under specified price, yield, and cost conditions. Solving this equivalence condition yields a facility of approximately 17,502 ft^2, which then serves as the baseline unit for all subsequent analyses. The analytical framework incorporates empirical data from published scientific literature, USDA, Kansas State University's Department of Agricultural Economics' Extension Website, AgManager.info, and construction quotes for controlled environment agriculture (CEA). The initial activity involved constructing a deterministic 20-year discounted cash flow (DCF) model using the historical data on prices, yields, operating costs, and information on capital costs. Stochastic simulation is then applied to this deterministic foundation to characterize the probability distribution of economic outcomes under simultaneous parameter uncertainty.

The analysis is conducted in four sequential stages. First, a baseline input parameter set is established for both production and financial variables, using median values from the literature where ranges are reported across multiple studies. Second, four one-way sensitivity scenarios (Scenarios A–D) apply adverse shocks of based on the variables' estimated standard deviations to individual parameters to determine their marginal effects on investment viability. Third, four two-way sensitivity analyses (Scenarios E–H) generate heatmaps of net present value (NPV) outcomes across paired parameter shocks, thereby revealing interaction effects between the most critical drivers. Fourth, a 10,000-iteration Monte Carlo simulation draws all uncertain inputs from their empirical distributions to produce the joint probability distribution of NPV and associated risk metrics.

All financial performance metrics, including NPV, IRR, payback period, and benefit–cost ratio (BCR), are calculated using a weighted average cost of capital (WACC) of 8% as the discount rate. Sensitivity and Monte Carlo analyses systematically adjust the inputs to delineate the feasible operating space, quantify downside risk, and identify the critical success factors that most significantly influence project viability.

3.1 Typical Farmer

The "Typical Farmer" may be conceived of as the one with characteristics most common across all farmers. Typical differs from the average in the sense that the average risks not being representative of any of the set from which it is estimated whereas the typical will always be like the majority of elements in the set from which it is determined. Let us illustrate with a set A defined by the following numbers: A = {1, 1, 1, 1, 1, 10, 20}. The average of A is 5 (= 35/7) but the typical in A is 1.

The typical farmer establishes the financial and water use baseline for evaluating the greenhouse tomato enterprise. This model incorporates three primary inputs: regional crop acreage shares, which determine portfolio composition; per-acre irrigation requirements from published enterprise budgets, which inform total water withdrawal; and a typical farm size, which scales per-acre estimates to the whole-farm level. Net farm income for the typical farmer is not calculated from the enterprise budget but is instead calculated as the average of the modal incomes over five consecutive years (2000-2024) from the Kansas Farm Management

Association (KFMA) for southwest Kansas, as detailed in Section 3.1.2. The enterprise budget is used exclusively to estimate crop-specific water consumption.

3.1.1 Crop Portfolio and Acreage Allocation

The crop portfolio of the typical farm reflects the relative importance of the four principal irrigated commodities in Kansas, as reported by the United States Department of Agriculture National Agricultural Statistics Service (USDA NASS, 2025). Wheat, corn, soybeans, and grain sorghum together account for dominant share of irrigated cropland in the High Plains. Statewide planted acreage figures are used as proxies for the relative crop composition of southwest Kansas in the absence of county-level disaggregated irrigated acreage by crop. Table 3.1 reports the statewide totals from which portfolio weights are derived.

Table 3.1: Crop Portfolio and Acreage Shares

Crop	Kansas Planted Acres (Million)	Portfolio Share (%)
Wheat	7.60	35.4
Corn	6.30	29.4
Soybeans	4.55	21.2
Grain Sorghum	3.00	14.0
Total	21.45	100.0

The portfolio share assigned to each crop is computed as its statewide acreage divided by the total state acreage across all four commodities:

$$s_c = \frac{A_c}{\sum A_c} \ \forall\, c = 1, 2, \dots, 4,$$

where s_c is the portfolio share of crop c; A_c is Kansas statewide planted acreage of crop c.

Acreage allocated to each crop on the typical farm is then obtained by multiplying its portfolio share with total operated farm size, F:

$$A_{c_c} = F s_c.$$

3.1.2 Typical Farm Size and Benchmark Income

The typical farm size in southwestern Kansas was estimated at 1,467.21 acres. This was the 'modal' farm size across the primary irrigated crops in all southwest Kansas counties. It is consistently applied in all calculations: per-acre costs, revenues, and water requirements are scaled to this farm size to estimate total farm income and water use.

Setting the typical net farm income benchmark started with the reported average farm size and the average net farm income for southwest members of Kansas Farm Management Association producing corn, soy, wheat, and sorghum (KFMA, 2025). These two numbers were used to estimate the average net farm income for each year. Assuming that the previously estimated typical farm acreage in southwest Kansas does not change, Table 3.2 shows that the estimated typical farm income from 2020 to 2024 as the product of the estimated average net farm income per acre and the typical farmer's total acreage estimated above. The benchmark net farm income of $147,853 was the average of the typical farmer's net farm income between 2020 and 2024. Its estimated standard deviation was approximately $72,210.

Table 3.2: Benchmark Net Farm Income Calculation

Year	Average KFMA SW KS			Typical Farmer Net Farm Income ($)
	Net Farm Income ($)	Average Crop Acreage (Acre)	Net Farm Income ($/acre)	
2020	173,972	1,796	97	142,123
2021	319,180	1,774	180	263,982
2022	177,696	1,653	108	157,724
2023	100,618	1,644	61	89,798
2024	98,583	1,689	58	85,638
5-Yr Average	174,010	1,711	101	147,853
Std. Dev. (σ)	89,671	70	49	72,210

3.1.3 Water Consumption Estimation

Per-acre irrigation requirements for each crop are obtained from the 2026 KSU AgManager irrigated enterprise budgets for the middle scenario in southwest Kansas (KFMA, 2025). Total annual irrigation water withdrawals, W, from the Ogallala Aquifer are computed analogously:

$$W\ (ac - ft)\ =\ \Sigma_c\ [(W_c\ \div\ 12)\ \times\ Acres_c]$$

Where W_c is the irrigation requirement for crop c in acre-inches per acre and the factor of twelve converts acre-inches to acre-feet. The resulting total water withdrawal figure serves as the denominator for the gross revenue per acre-foot and net farm income per acre-foot metrics employed in the water productivity analysis.

Table 3.3: Crop Water Requirements and Total Ogallala Aquifer Withdrawals

Crop	**Water Req. (ac-in/ac)**	**Allocated Acres**	**Total Water (ac-ft)**
Wheat (Durum)	6.0	519.9	259.9
Corn	15.0	430.9	538.7
Soybeans	11.0	311.2	285.3
Grain Sorghum	12.0	205.2	205.2
Total	—	**1,467.2**	**1,289.1**

The resulting total annual water withdrawal of 1,289.1 acre-feet serves as the denominator for the gross revenue per acre-foot and net farm income per acre-foot metrics employed in the water productivity comparison in Section 4.8. This figure represents the volume of Ogallala groundwater annually extracted to sustain the representative farm's irrigated crop mix under the 2026 price and cost environment and provides the benchmark against which the water use of the greenhouse enterprise is evaluated.

3.2 Greenhouse Tomato Production – Economic Model

The purpose of the economic model of the greenhouse tomato production is to find an income-preserving production that simultaneously contributes significantly to water conservation. The economic model employed here consists of three interconnected components: a production sub-model that converts physical parameters (facility area, plant density, and yield) into annual output; an income statement sub-model that calculates gross revenue, operating costs, depreciation, and net income for each of the twenty operating years; and a capital budgeting sub-model that compiles annual net cash flows and discounts them to present value. These sub-models are solved sequentially for the base scenario and re-solved for each sensitivity scenario and Monte Carlo simulations.

3.2.1 Production System Assumptions

Recall the minimum greenhouse area expected to produce the benchmark income was estimated as 17,502ft². The greenhouse itself was assumed to be high-technology hydroponic facility employing Dutch-style high-wire growing systems with supplemental LED lighting, precision climate control, and CO_2 enrichment. This configuration represents the prevailing commercial standard for high-yielding soilless tomato production in the United States and Western Europe and constitutes an appropriate benchmark for a state-of-the-art technology that can realistically be deployed in a greenfield operation.

Assuming 85% of the greenhouse footprint as growing area, a plant density of 0.27 plant per square foot is set. Total plant for the baseline is, therefore, given by the following equation:

$$N_{plants} = 0.27\, plants/ft^2 \times 85\% \times (17{,}502\, ft^2) = 4{,}012\, plants$$

The baseline yield is set at 15.43 lb/ft²/yr. Net production, applying a 5% shrinkage (δ_S) allowance (Thorsen et al., 2021), is given by:

$$Q_t = Y_{base} \times A \times (1 - \delta_s) \; for \; t = 1,2,3, \dots ,20$$

Where Y_{base} is the baseline yield (lb/ft²/yr), A is the facility productive area (ft²), and δ_s is as defined.

3.2.2 Capital Expenditure (CAPEX) Assumptions

Initial capital costs were estimated using $\$98/ft^2$, representing a midpoint of reported high-tech greenhouse construction and consistent with the range of \$50-150/ ft^2. Stein (2021) notes that this cost covers components such as structure and glazing, climate control systems, energy systems, automation and smart technologies, hydroponics and fertigation, internal equipment and supplemental lighting, civil works and foundations, utilities infrastructure, and engineering, design, permitting, and contingency. The total initial capital expenditure for one acre facility is:

$$C_0 = \$98 \, / ft^2 \times 17{,}502 \, ft^2 = \$1{,}718{,}747$$

We employ the straight line depreciation method, such that for a 20-year useful life facility, the depreciation, D_t, with a zero salvage value (SV_{20}), is as follows::

$$D_t = \frac{C_0 - SV_{20}}{T} = \frac{\$1{,}718{,}747 - \$0}{20} = \$85{,}937 \, / \, yr$$

3.2.3 Operating Expenditure Assumptions

Operating expenses (OPEX) in greenhouse tomato production are primarily categorized into labor, energy, crop inputs, and auxiliary services. Labor constitutes the largest expenditure, representing between 24.7% and 59% of total costs (Baytorun & Zaimoğlu, 2023; Braynon et al., 2026; Peña et al., 2022). This large share of labor results from the manual demands of nursery activities, transplanting, pruning, pollination, and harvesting. Energy and utilities represent the second-largest cost segment, between 18% and 20%. They include heating fuels, geothermal fees, and electricity for climate control and irrigation systems. Crop inputs, such as seeds, substrates, and fertilizers, together with essential services and packaging including biological pollinators, Good Agricultural Practices (GAP) compliance and other regulatory requirements, and maintenance comprise the remaining critical components of the operational budget. The base assumption for OPEX was $14.22/ft^2/year.

Total OPEX was calculated as:

$$OPEX_t = \$14.22/ft^2/yr \times 85\% \times 17{,}502\ ft^2 = \$211{,}547$$

3.3 Financial Model Assumptions

3.3.1 Discounted Cash Flow

The financial model employs a standard 20-year discounted cash flow framework in which Year 0 represents the capital investment period and Years 1–20 represent operational cash flows. All cash flows are discounted to present value using a WACC of 8%. The net cash flow in each period, t, is the sum of operating cash flow (OCF) and investing cash flow (ICF) in that time period, i.e.,:

$$NCF_t = OCF_t + ICF_t$$

Net income in each operating year is derived from the project income statement. Earnings before interest and taxes (EBIT) are computed as gross revenue(GR) less total operating expenditure (OPEX) and depreciation (D):

$$EBIT_t = GR_t - OPEX_t - D_t$$

After-tax net income (NI) is obtained by applying a blended federal and state corporate tax rate, τ, of 28%:

$$NI_t = EBIT_t \times (1 - \tau) \quad where\ \tau = 0.28$$

3.3.2 Financial Indicators

Net Present Value (NPV), Internal Rate of Return (IRR), Payback Period (PBP), and Benefit Cost Ratio (BCR) were used to assess the feasibility of the production of tomato under greenhouse in southwest Kansas. Net Present Value (NPV) represents the present value of cash flows generated from a study over a specified period, discounted at a predetermined rate, minus the initial investment. NPV is calculated as:

$$NPV = \sum_{t=1}^{T} \left(\frac{CF_t}{(1+r)^t}\right) - C_o,$$

where CF_t represents the cash flow at time t and r represents the discount rate. C_o represents the initial investment. By having a positive NPV, the study can be considered as feasible otherwise if the NPV is negative the project will not generate enough cash flow to cover the initial investment. The internal rate of return (IRR) is the discount rate that equates the net present value to zero and may be defined as:

$$NPV = 0 = \sum_{t=1}^{T} \left(\frac{CF_t}{(1+IRR)^t}\right) - C_o$$

The payback period (PBP) is the earliest year, t*, at which cumulative undiscounted net cash flows is equal to or greater than the initial investment. That is,

$$PBP_{t*} = \min \left\{ t: \sum_{t=1}^{t} C\,F_t \geq C\_0 \right\}$$

The Benefit-Cost Ratio (BCR) is the ratio of the present value of all cash inflows from the investment to the cash outflows. A BCR greater than 1.0 demonstrates that a project's benefits surpass its costs, thereby offering a scale-independent measure of value useful for comparisons. The BCR may be defined as follows:

$$BCR = \frac{\sum_{t=0}^{T} \frac{R_t}{(1+d)^t}}{\sum_{t=0}^{T} \frac{C_t}{(1+d)^t}},$$

where R is revenue from investment operations, C is cost associated with investment operations and all other variables are as defined.

3.4 Breakeven Analysis

Breakeven analysis may be conducted for all critical parameters of the investment. It is typically performed for output or scale. Therefore, the discounted breakeven scale or output is defined as the minimum output, Y*, at specified prices and costs required for the discounted sum of net price to equal investment cost. That is:

$$Y^* \left(\sum_{t=0}^{T} \frac{(P-w)}{(1+d)^{-t}} \right) = \mathrm{C}_0$$

$$Y^* = \frac{C_0}{\sum_{t=0}^{T} \frac{(P-w)}{(1+d)^{-t}}}$$

These thresholds establish the project's safety margin under unfavorable market or production conditions and directly connect the deterministic financial model to risk characterization within the Monte Carlo simulation.

3.5 Sensitivity Analysis

Sensitivity analysis quantifies the impact of changes in individual model parameters on key performance metrics, assuming all other factors remain constant. This study employs two analytical tiers: one-way analysis (Scenarios A–D), which varies a single parameter to isolate its marginal effect on investment viability, and two-way analysis (Scenarios E–H), which simultaneously varies two parameters to reveal interaction effects. In both tiers, shocks are calibrated as proportional to the empirical standard deviation, derived from the literature informing the baseline estimate for each variable. All scenarios assess the impact of adverse shocks on the two primary revenue drivers (price and yield) and upward shocks to the two primary cost drivers (OPEX and CAPEX). Each parameter is shocked at two magnitudes.

3.6 Monte Carlo Simulation

Monte Carlo simulation is a numerical technique that utilizes random sampling to quantify the effects of input uncertainty on a range of potential outcomes. By executing thousands of randomized iterations, the simulation moves beyond simple best-case or worst-case scenarios. It generates a probability density function that quantifies the likelihood of different outcomes and offers a deeper understanding of the project's risk profile (J. Li, 2025).

For the Monte Carlo simulations performed for this study, a normal distribution for 10,000 iterations was used for four parameters of interest: price, yield, OPEX and CAPEX. The NPV for each iteration is computed as:

$$NPV_i = \sum_{t=0}^{20} \frac{NCF_t(P_i,\ Y_i,\ OPEX_i,\ CAPEX_i)}{(1.08)^t}$$

The following risk metrics are computed from the simulated NPV distribution to characterize investment viability and downside exposure. The mean NPV provides the central tendency of the unconditional outcome distribution:

$$\overline{NPV} = \frac{1}{n}\sum_{i = 1}^{n} NPV_i \quad where\ n = 10{,}000$$

The standard deviation of the simulated NPV distribution quantifies total outcome variability:

$$\sigma_{NPV} = \sqrt{\frac{1}{n - 1}\sum_{i = 1}^{n} (NPV_i - NPV)^2}$$

Value at Risk at the 95% confidence level (VaR_{95}) is the 5th percentile of the simulated NPV distribution, representing the maximum loss expected in the worst 5% of outcomes:

$$VaR_{95\%} = 5th\ percentile\ of\ \{NPV_i\}$$

The probability of investment viability is the proportion of simulated iterations yielding a non-negative NPV:

$$P(NPV \geq 0) = \frac{\#\{NPV_i \geq 0\}}{n} \times 100\%.$$

Chapter 4 - Results and Discussion

This chapter presents and discusses the results of the empirical analyses described in Chapter 3. The discussion is organized into seven sections. Section 4.1 states the key baseline parameters for the representative southwest Kansas irrigated grain farm established in Chapter 3, which serve as the reference point for the comparative analysis. Section 4.2 details the foundational parameters and capital structure of the greenhouse tomato enterprise, providing the basis for subsequent financial analysis. Section 4.3 reports the income and cash flow statements under baseline assumptions. Section 4.4 evaluates the financial performance of the greenhouse enterprise using standard investment metrics, including net present value, internal rate of return, payback period, and benefit-cost ratio. Section 4.5 presents the net present value (NPV) breakeven thresholds for the four principal uncertain variables. Section 4.6 examines the sensitivity of financial outcomes to adverse shocks in price, yield, operating expenditure, and capital expenditure, first through one-way analysis and then through simultaneous two-way shocks. Section 4.7 presents the results of the Monte Carlo simulation, which characterizes the distribution of possible NPV outcomes under joint parameter uncertainty. Section 4.8 synthesizes the findings through a comparative analysis of the traditional farm and greenhouse enterprises, with particular attention to income generation and water productivity per acre-foot of Ogallala water applied.

4.1 Typical Farmer Baseline

The typical southwest Kansas irrigated grain farm was fully characterized in Chapter 3. Three parameters from that characterization serve as direct inputs to the analyses' results presented in this chapter and are therefore restated here for reference. First, the farm operates 1,467.21 acres under a four-crop portfolio of wheat, corn, soybeans, and grain sorghum, with acreage allocated across crops according to USDA NASS statewide planted area shares. Second, the farm withdraws a total of 1,289.1 acre-feet of Ogallala groundwater annually, computed by applying KSU AgManager 2026 per-acre irrigation requirements to the allocated crop acreage. Third, the five-year average net farm income of $147,853, derived from KFMA southwest Kansas data for 2020 through 2024 and scaled to the representative farm size, serves as the income-equivalence target that determines the 17,502 ft² greenhouse facility size analyzed throughout this chapter. All three figures are taken as given for the purposes of this chapter; the reader is referred to Chapter 3 for the full derivation and data sources underlying each.

4.2 Greenhouse Tomato- Economic Feasibility

This chapter presents and interprets the results of a 20-year discounted cash flow (DCF) feasibility analysis for a high-technology hydroponic greenhouse tomato enterprise in southwest Kansas, sized at 17,502 ft² to match the income-equivalence target established in Chapter 3. The analysis is structured to align with the four secondary research objectives outlined in Chapter 1: (1) establishing baseline operational and financial parameters; (2) constructing a deterministic income statement and cash flow model; (3) evaluating financial viability using key investment metrics, breakeven analysis, and sensitivity analysis; and (4) assessing downside risk through stochastic Monte Carlo simulation. The analysis utilizes a weighted average cost of capital (WACC) of 8.0% and an effective corporate tax rate of 28%.

4.2.1 Baseline Model Parameters and Capital Structure .

Prior to evaluating financial performance, it is necessary to examine the foundational parameters that guide the model's behavior. Table 4.1 presents the complete set of input assumptions.

Project Size: The greenhouse facility encompasses 17,502 ft², calculated as the production area necessary for Year 1 net income to match the five-year KFMA average net farm income benchmark of $147,853 established in Chapter 3. Of this total area, 85%, or 14,877 ft², is designated as productive growing space. The remaining area is allocated to corridors, mechanical rooms, climate control equipment, and post-harvest packing and handling, in accordance with standard commercial greenhouse layout practices (Vallejo et al., 2018). At a plant density of 0.27 plants/ft² (Kim & Kubota, 2025), the facility accommodates 4,012 tomato plants. This density is conservative relative to higher-intensity operations reported in the literature, which may reach 0.33 plants/ft² (Torres-Quezada & Gandini-Taveras, 2023) or 0.41 plants/ft² (Qiu et al., 2013). The foregoing are summarized in Table 4.1.

Table 4.1. Project Size Parameters

Parameter	**Value**
Total Greenhouse Footprint (ft²)	17,502
Growing Area (85% of footprint, ft²)	14,877
Plant Density (plants/ft²)	0.27
Total Plants	4,012

Capital Expenditure: The total initial capital expenditure of $1,718,747 is computed as the product of the 17,502 ft² footprint and a per-square-foot cost of $98.20. This, as reported, represents the mean from multiple vendor quotes and consistent with the $50–$150/ft² range reported in the CEA literature (Mills, 2025; Stein, 2021b). This per-unit cost encompasses all components of a turnkey high-technology hydroponic greenhouse, including structure and glazing, climate control systems, energy infrastructure, automation and smart technologies, hydroponics and fertigation equipment, supplemental LED lighting, civil works and foundations, utilities connections, and engineering, design, permitting, and contingency allowances. The standard deviation of $57.55/ft² reflects the significant variation in construction costs across regions and technology configurations and informs the CAPEX distribution used in the sensitivity and Monte Carlo simulations.

Depreciation is computed using the straight-line method over a 20-year useful life, yielding an annual charge of $85,937. A 5% replacement capital expenditure is modeled at Years 5, 10, and 15, consistent with the five-year refresh cycle recommended for precision sensors, automated systems, and LED lighting components in high-technology greenhouse operations (Morella et al., 2023); Thomas & Weiss, 2021). Salvage value is assumed to be zero at the end of the project horizon, reflecting the specialized nature of greenhouse infrastructure. The CAPEX assumptions are summarized in Table 4.2.

Table 4.2 Capital Expenditure Parameters

Parameter	Value
CAPEX per ft²	$98.20/ft²
Total Initial CAPEX ($)	$1,718,747
Replacement CAPEX (5% at Years 5, 10, 15)	$85,937 per event
Useful Life (years)	20 years
Annual Depreciation (straight-line)	$85,937/yr

Operating Expenditure: Year 1 total operating expenditures of $211,547 are computed as the product of the mean OPEX rate of $14.22/ft²/yr and the productive growing area of 14,877 ft². This rate represents the mean of per-square-foot operating cost estimates drawn from the CEA literature and encompasses the four principal cost categories: labor, which constitutes the largest component at 24.7 to 59% of total OPEX (Baytorun & Zaimoğlu, 2023; Braynon et al., 2026; Peña et al., 2022); energy and utilities at approximately 18–20% of total costs, including electricity for climate control, supplemental lighting, and irrigation pumping (Braynon et al., 2026; Dekamin et al., 2024); crop inputs including seeds, growing substrates, and nutrient solutions; and auxiliary services including biological pollination, Good Agricultural Practices compliance, packaging, and routine maintenance. The standard deviation of $13.53/ft²/yr reflects the wide heterogeneity in operating cost structures across greenhouse operations of different scales, technology intensities, and geographic locations, and constitutes the primary source of cost-side uncertainty in the stochastic analyses. Operating costs are assumed to escalate at 2.47% per annum, reflecting the blended rate of labor and energy cost inflation. These parameter assumptions are summarized in Table 4.3.

Table 4.3. Operating Expenditure Parameters

Parameter	Value
OPEX per ft²/yr (Year 1)	$14.22/ft²/yr
Total OPEX Year 1 ($)	$211,547
OPEX Escalation Rate	2.47%/yr

Revenue and Pricing: The baseline Year 1 selling price of $2.31/lb represents the average of wholesale greenhouse tomato prices reported in the controlled environment agriculture (CEA) literature. Pricing definitions in the reviewed sources are not consistently specified and may include farm-gate, FOB shipping-point, or delivered wholesale prices. Accordingly, this analysis treats the reported price as a reasonable approximation of the producer's gross revenue, without explicitly modeling downstream transportation or distribution costs. This assumption is supported by observed U.S. retail price ranges for greenhouse-grown specialty tomatoes, including vine-ripe, grape, and cherry varieties, which range from $0.99 to over $3.99 per pound depending on format, retail channel, and season (Simonne et al., 2006). The baseline price of $2.31 per pound falls within this documented market range. The actual price achievable by a southwest Kansas producer would depend on the specific tomato variety and market channel selected. The standard deviation of $1.21/lb reflects the inherent price volatility of the fresh specialty tomato market, which is influenced by seasonal supply fluctuations, import competition from Mexico, and evolving consumer preferences for premium vine-ripe and specialty formats (Cui et al., 2022); (Simonne et al., 2006). Prices are projected to increase at an average annual rate of 2.00%, in line with the long-term food price inflation rate in the United States, rising from $2.31 per pound in Year 1 to $3.36 per pound by Year 20. With production volume held constant, gross revenue will also grow at the same 2.00% annual rate. These assumptions are summarized in Table 4.4.

Table 4.4. Revenue and Pricing Parameters

Parameter	Value
Baseline Selling Price (Year 1)	$2.31/lb
Price Escalation Rate	2.00%/yr
Year 20 Selling Price (projected)	$3.36/lb

Yield and Production: The baseline yield of 15.44 lb/ft²/yr (approximately 74.6 kg/m²/yr) reflects the mean yield reported in high-technology hydroponic greenhouse tomato operations within the controlled environment agriculture (CEA) literature, with a standard deviation of 2.36 lb/ft²/yr. This yield is conservative compared to the upper range of published commercial yields. Operations utilizing optimal CO_2 enrichment, supplemental LED lighting, and advanced crop management have achieved yields of 60.2 to 71.6 kg/m² per cycle or higher (Maureira et al., 2022a). Therefore, the selected baseline is considered achievable for a well-managed new-build facility in southwest Kansas. Gross annual production is calculated as 229,632 lb/yr, based on the baseline yield and a growing area of 14,877 ft². Applying a post-harvest packout loss allowance of 5% (Thorsen et al., 2021) results in a net saleable production of 218,151 lb/yr, which is used as the revenue-generating output in the income and cash flow model. The yield is assumed to remain constant throughout the 20-year analysis horizon under base-case assumptions. The foregoing assumptions are summarized in Table 4.5.

Table 4.5. Yield and Production Parameters

Parameter	**Value**
Annual Yield (lb/ft²/yr)	15.44
Gross Annual Production (lb/yr)	229,632
Packout Loss (5%)	11,482 lb/yr
Net Annual Production (lb/yr)	218,151

Financial Assumptions: All cash flows are discounted at a weighted average cost of capital (WACC) of 8.0%, which represents the combined cost of debt and equity financing for a capital-intensive agricultural investment of this magnitude. This rate aligns with WACC assumptions used in comparable greenhouse feasibility studies in the literature (Ahamed et al., 2019; Michalis et al., 2023b) and approximates the long-term real return on agricultural capital investments in the United States. A corporate tax rate of 28% is applied to positive earnings before interest and taxes (EBIT) in each operating year, representing the combined federal and state tax burden for a corporate greenhouse operator in Kansas. The analysis period of 20 years reflects the expected useful life of the facility and is consistent with standard practice for long-lived agricultural infrastructure investments. The salvage value is set to zero at the end of Year 20, conservatively accounting for the specialized nature of greenhouse infrastructure and the uncertainty regarding residual values in an emerging regional industry. The foregoing is summarized in Table 4.6.

Table 4.6. Financial Assumptions

Parameter	Value
WACC (Discount Rate)	8.0%
Corporate Tax Rate	28.0%
Analysis Horizon	20 years
Salvage Value	$0

Table 4.7 presents the distributional parameters for the four principal uncertain variables. These broad distributions have significant implications for sensitivity and Monte Carlo analyses.

Table 4.7. Input Parameters and Shock Levels

Parameter	Mean (μ)	Std Dev (σ)
Selling Price ($/lb)	$2.31	$1.21
Annual Yield (lb/ft²/yr)	15.44	2.36
OPEX ($/ft²/yr)	$14.22	$13.53
CAPEX ($/ft²)	$98.2	$57.55

4.3 Income and Cash Flow Statements

Figure 4.1 illustrates the projected 20-year undiscounted financial performance of the greenhouse enterprise, displaying annual income metrics in dollars on the left axis and the EBITDA margin trend on the right axis. Price is assumed to grow at an average annual rate of 2%, starting at $2.31 lb^{-1} in Year 1 and ending at $3.36 lb^{-1} in Year 20. As both yield and production area remain constant throughout the analysis period, gross revenue rises at the same rate as price, increasing from $502,833 in Year 1 to $732,539 in Year 20. Total operating expenses (OPEX) are determined by the unit cost of production applied to the fixed growing area of 14,877 square feet. Consequently, operating costs increase solely due to the assumed inflation rate of 2.47% per year, rising from $14.22 per square foot in Year 1 to $22.73 per square foot in Year 20, and in aggregate from $211,548 to $338,192 over the project duration. Since OPEX grows at a faster rate than revenue, the EBITDA margin declines steadily from 57.93% in Year 1 to 53.83% in Year 20, although absolute EBITDA increases from $291,286 to $394,344. Net income demonstrates a consistent upward trend, increasing from $147,851 in Year 1, which serves as the reference value for the income-equivalence condition established in Chapter 3, to $222,053 in Year 20, representing a 50.2% increase over the analysis period.

Figure 4.1: Projected Undiscounted Greenhouse Tomato Performance (Year 1-20)

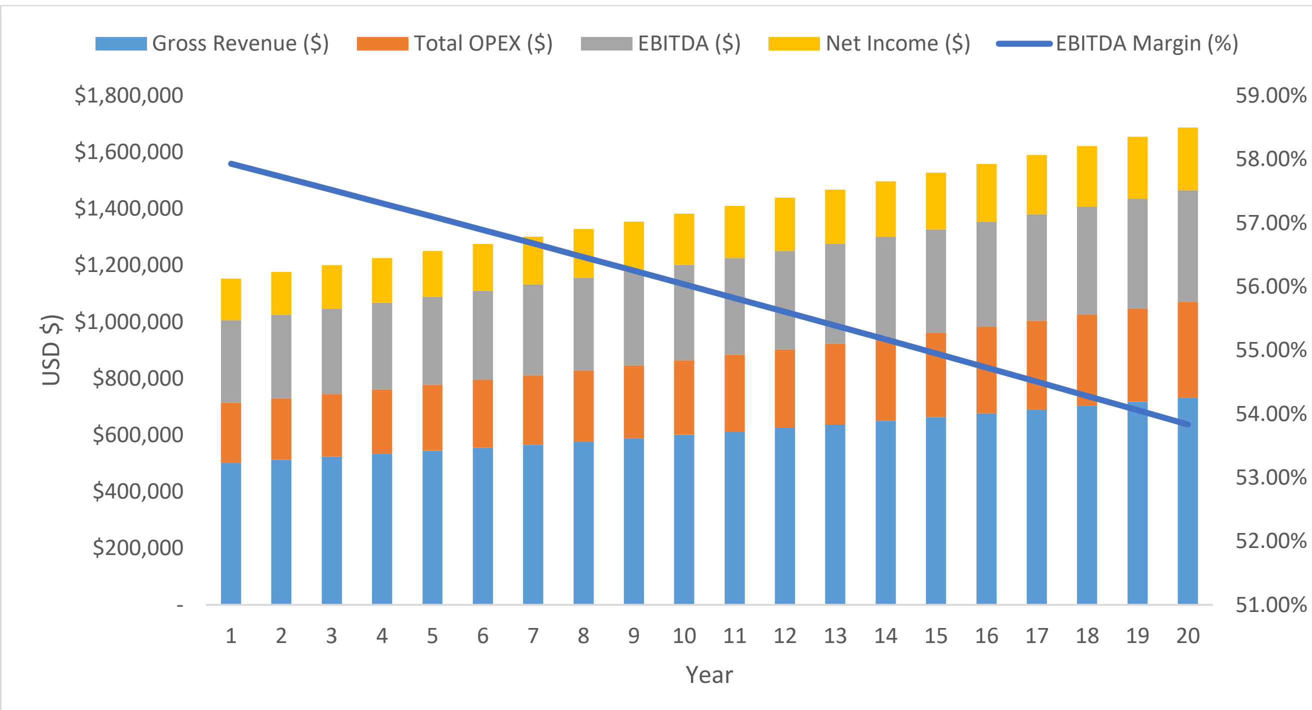


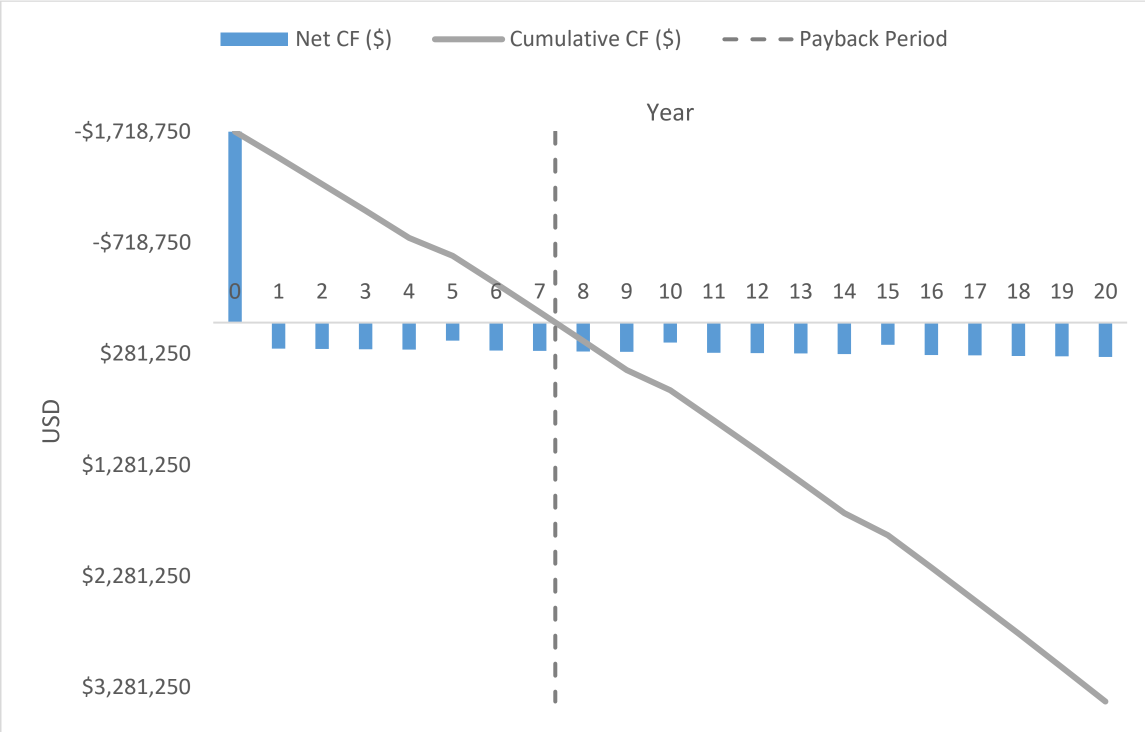
Table 4.8 illustrates that the cumulative cash flow profile is typical of a capital-intensive investment with robust operational cash generation. An initial large negative outflow in Year 0 ($1,718,747) is followed by consistently positive annual net cash flows, which gradually reduce the initial deficit. Annual operating cash flows increase from $233,790 in Year 1 to $307,992 in Year 20, representing a 31.7% rise over the project duration. This growth is attributed to

compounding revenue gains outpacing escalating costs. Also, a 5% replacement CAPEX was used. According to Thomas & Weiss (2021), the cost to replace assets in complex manufacturing environments typically ranges from 1.8% to 5.0%. To maintain a competitive and technologically advanced facility, the model adopts a five-year replacement cycle for all precision sensors and automated systems. This proactive refresh interval, as demonstrated by Morella et al. (2023), ensures that the initial capital investment is safeguarded by consistently updated, efficiency-enhancing hardware.

Table 4.8. Cash Flow Statement

Year	Operating CF	Investing CF	Net CF	Cumulative CF
0	—	−$1,718,747	−$1,718,747	($1,718,747)
1	$233,790	$ 0	$ 233,790	($1,484,959)
2	$237,222	$ 0	$ 237,222	($1,247,735)
5	$247,820	−$ 85,937	$ 402,905	$600,906
10	$266,515	−$ 85,937	$ 449,433	$607,827
15	$286,551	−$ 85,937	$ 499,300	$1,914,033
20	$307,992	$ 0	$ 307,992	$3,410,544

Figure 4.2: Annual Net Cash Flow and Cumulative Cash Flow (Year 0-20)



4.4 Financial Performance Metrics

Having established the baseline operational parameters and constructed the 20-year income and cash flow statements, this section assesses the financial viability of the greenhouse enterprise using four standard investment appraisal metrics: net present value (NPV), internal rate of return (IRR), payback period (PBP), and benefit-cost ratio (BCR). Each metric captures a distinct aspect of financial performance. NPV measures value creation in absolute terms, IRR indicates the rate of return on invested capital, PBP reflects the time required to recover the initial investment, and BCR quantifies the ratio of discounted benefits to discounted costs. Collectively, these metrics offer a comprehensive and internally consistent evaluation of whether the 17,502 ft² greenhouse tomato enterprise represents a financially sound investment under baseline assumptions. All calculations employ a weighted average cost of capital (WACC) of 8.0% as the discount rate and an effective corporate tax rate of 28%.

Table 4.9. Key Financial Performance Metrics

Financial Metric	Value
Net Present Value (NPV)	$706,705
Internal Rate of Return (IRR)	12.88%
Payback Period (PBP)	7.36 yrs
Benefit-Cost Ratio (BCR)	1.17

The base-case net present value (NPV) of $706,705 is positive, meeting the primary financial feasibility criterion. This result shows the project is expected to generate returns above the 8% cost of capital over its 20-year life, creating economic value for the investor. In other words, a positive net present value means the project is feasible under current assumptions. This outcome aligns with several economic evaluations in the literature that confirm the viability of greenhouse tomato ventures. For example, year-round production in the Canadian Prairies achieved a comparable NPV of approximately CAD$1.9 million and a benefit–cost ratio of 1.38 (Ahamed et al., 2019). Additional studies from Western Greece and Oman indicate that hydroponic and multi-crop greenhouse systems are economically viable across most price and cost scenarios, with stochastic simulations frequently indicating a high probability of positive outcomes (Ishag & Al Rawahy, 2018; Michalis et al., 2023c)

The internal rate of return (IRR) of 12.88% exceeds the weighted average cost of capital (WACC) of 8.0%, indicating that the proposed greenhouse tomato operation generates a return on invested capital that surpasses the minimum rate required to compensate investors and cover the opportunity cost of capital. The payback period indicates that the total initial capital investment is fully recovered from the project's cumulative net cash flows approximately 7.36 years.

The benefit–cost ratio (BCR) of 1.17 indicates that the greenhouse project generates approximately $1.17 in discounted benefits for every $1.00 of discounted costs over the project horizon. Because the BCR exceeds unity, the project satisfies the standard economic feasibility criterion. However, the relatively modest margin above 1.0 suggests that profitability is sensitive to changes in key parameters such as output price, operating costs, and the cost of capital. This result is consistent with the positive net present value (NPV) of $706,705 and an internal rate of return (IRR) of 12.88%, confirming that the project is viable but subject to risk under base-case assumptions.

4.5 NPV Breakeven Analysis

Table 4.10 presents the breakeven values for each of the four principal uncertain variables under discounted cash flow conditions. The breakeven value for each parameter indicates the threshold at which the project's NPV equals zero, assuming all other inputs remain at their base case levels. The difference between each base case value and its corresponding breakeven threshold defines the project's safety margin, which quantifies the extent to which adverse deviations in that variable can be tolerated before the investment fails to recover its cost of capital.

Table 4.10. Breakeven Analysis Summary

Variable	Base Value	Breakeven Value	Safety Margin (%)
Selling Price ($/lb)	$2.31	$1.91	17.3% below base
Annual Yield (lb/ft^2/yr)	15.44	12.78	17.2% below base
OPEX ($/ft^2/yr)	$14.22	$19.81	39.3% above base
CAPEX ($/ft^2)	$98.20	$141.36	43.9% above base

The price breakeven value of $1.91/lb demonstrates that the enterprise can tolerate a selling price reduction of $0.40/lb, corresponding to a safety margin of 17.3% below the base case mean, before the net present value (NPV) becomes negative. This buffer should be evaluated in the context of underlying price variability. With an assumed price standard deviation of \$1.21/lb, the breakeven decline of \$0.40 constitutes approximately one-third of a standard deviation below the mean price. Therefore, the breakeven threshold is relatively close in probabilistic terms and may be surpassed under plausible market conditions. Consequently, the enterprise exhibits high sensitivity to adverse price movements, and sustained price deterioration represents the most immediate threat to project viability.

The yield breakeven of 12.78 lb/ft^2/yr represents a reduction of 2.66 pounds per square foot per year, or a safety margin of 17.2% below the base case yield of 15.44 lb/ft^2/yr. The nearly identical safety margins for price and yield, 17.3% and 17.2% respectively, underscore that revenue-side risks, whether driven by market price or production volume, constitute the primary vulnerability of the enterprise.

The breakeven operating expenditure (OPEX) of \$19.81/ft^2/yr provides a headroom of about \$5.59 per square foot per year, representing a safety margin of 39.3% above the base case operating cost of \$14.22/ft^2/yr. Similarly, the capital expenditure (CAPEX) breakeven of \$141.36 per square foot offers a headroom of \$43.16/ft^2, equivalent to a safety margin of 43.9% above the base case capital cost of \$98.20/ft^2. These substantially wider margins on the cost side, compared to the revenue side, indicate that the enterprise is considerably more tolerant of cost overruns than of revenue shortfalls. Capital and operating expenditure risks, while present, are less immediately threatening to project viability than adverse movements in price or yield.

4.6 Sensitivity Analysis

We explore the sensitivity of the foregoing results to tomato prices and yields as well as operating and capital expenditures. The analysis introduces adverse shocks of 0.5σ and 0.67σ to each of these four principal uncertain variables, while maintaining all other parameters at their base case means. These shock magnitudes correspond to the 30.9th and 25th percentiles of the assumed normal distributions, respectively. Under the empirical properties of the input distributions, there is approximately a 31% probability of outcomes at or below the 0.5σ threshold and a 25% probability at or below the 0.67σ threshold. These scenarios do not represent tail events but rather plausible, recurring adverse conditions that a greenhouse operator could reasonably encounter. Their selection ensures that the sensitivity analysis addresses economically meaningful, rather than purely hypothetical, stress scenarios. The summary statistics for these variables are presented in Table 4.11.

Table 4.11: Iterative Shocks to Sensitivity Parameters

Statistic	**Price** ($/lb)	**Yield** (lb/ft²/yr)	**OPEX** ($/ft²/yr)	**CAPEX** ($/ft²)
Base	$2.31	15.44	$14.22	$98.20
Mean (SD)	$1.21	2.36	$13.53	$57.55
±0.5σ	$1.71	14.26	$20.99	$126.98
±0.67σ	$1.50	13.86	$23.29	$136.76
±1.0σ	$1.10	13.08	$27.75	$155.75

4.6.1 One-Way Sensitivity Analysis

Assuming that all variables are normally distributed, Table 4.12 presents the results of the four one-way sensitivity scenarios (Scenarios A through D), each introducing adverse shocks of 0.5σ and 0.67σ to a single uncertain variable while maintaining all others constant. The table reports NPV, IRR, and payback period for each scenario. Figure 4.4 presents these results as NPV deviation from the base case in a tornado chart.

For cost-side variables, namely OPEX and CAPEX, adverse shocks are applied as upward adjustments. The base case net present value (NPV) of $706,705, internal rate of return

(IRR) of 12.88%, undiscounted payback period of 7.36 years, and benefit-cost ratio (BCR) of 1.17 serve as the reference values for evaluating all scenario outcomes.

Table 4.12. One-Way Sensitivity Analysis Results (±0.50, 0.67 Standard Deviation (σ) Iterative Shocks)

Scenario	Shock Applied	NPV ($) 0.5σ	NPV ($) 0.67σ	IRR 0.5σ	IRR 0.67σ	PBP (yrs) 0.5σ	PBP (yrs) 0.67σ
A	Price − nσ	($363,234)	($730,044)	5.11%	1.71%	12.28	16.12
B	Yield − nσ	$393,662	$286,826	10.81%	10.07%	8.32	8.71
C	OPEX + nσ	($147,606)	($438,072)	6.86%	4.41%	10.71	12.77
D	CAPEX + nσ	$203,120	$31,888	9.14%	8.17%	9.31	9.97

Scenario A – Selling Price: Scenario A applies adverse price shocks of 0.5σ and 0.67σ to the selling price, reducing it from the base case mean of $2.31/lb to $1.71/lb and $1.50/lb, respectively. Under the 0.5σ shock, the project NPV declines from $706,705 to -$363,234, a deterioration of $1,069,939, representing a 151.4% decline relative to the base case. The IRR of 5.11% falls below the 8.0% WACC threshold, indicating that the project no longer compensates investors for the opportunity cost of capital. This outcome confirms that discounted returns are insufficient to justify the investment under the assumed price shock. Although a payback period of 12.28 years remains computable, indicating that the investment is eventually recovered in nominal terms, the sub-WACC IRR demonstrates that the recovery occurs at a rate insufficient to justify the capital commitment.

Under the 0.67σ shock, which corresponds to a 25% probability of occurrence under the normal distribution assumption, the NPV deteriorates further to negative $730,044, a decline of $1,436,749 from the base case. The IRR decreases to 1.71%, and the payback period extends to 16.12 years, representing more than 80% of the 20-year project horizon. The extended payback period and sharply reduced IRR further indicate severe erosion in project viability under this price scenario. The severity of these outcomes at the 25th percentile of the price distribution, meaning one in four years could produce prices at or below this level, underscores that selling price is the most critical and exposed value driver in the model. In contrast to cost variables, which can be partially managed through operational efficiency, the tomato price is generally determined by market forces and is, thus, assumed to be outside the operator's direct control. Having said that, it is possible to use ex-market relationships to increase control over price when the product has a certain degree of inherent special characteristics.

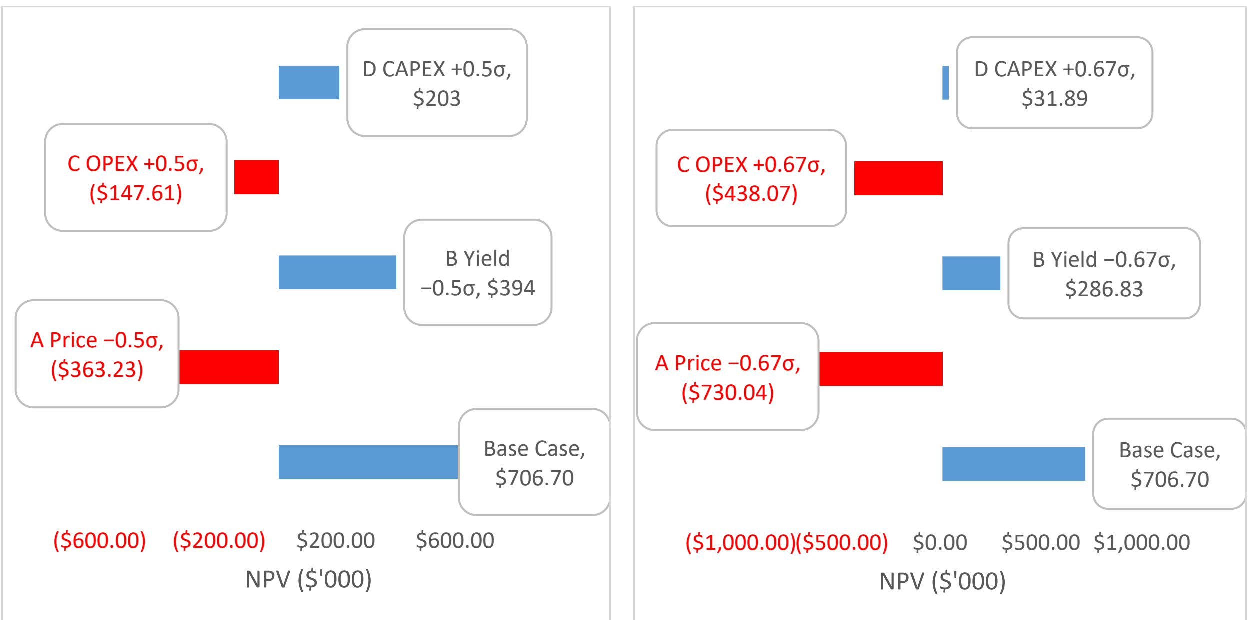
Scenario B –Yield: As with Scenario A, Scenario B introduces adverse yield shocks of 0.5σ and 0.67σ, reducing annual yield from 15.44 lb/ft²/yr to 14.26 lb/ft²/yr and 13.86 lb/ft²/yr, respectively, while holding price and all other variables at their baseline values. The enterprise remains financially viable under both shock levels. At the 0.5σ shock, net present value (NPV) declines to $393,662, representing a reduction of $313,043 (44.3% below the base case). The internal rate of return (IRR) of 10.81% remains above the weighted average cost of capital (WACC), payback period extends modestly to 8.32 years. The IRR remains above the weighted average cost of capital, and the payback period remains within a commercially acceptable range. Under the 0.67σ shock, NPV decreases further to $286,826 and IRR to 10.07%, yet both metrics remain positive and above the cost of capital threshold. The payback period of 8.71 years and IRR of 10.07% confirm that financial viability is preserved even at the 25th percentile of the yield distribution.

The relative resilience of the enterprise to yield shocks, compared to the pronounced impact of price shocks, reflects the structural advantage of constant-area, controlled-environment production. In greenhouse conditions, yield variability is substantially lower than in open-field agriculture because growing conditions are managed rather than weather-dependent. The standard deviation of 2.36 lb/ft²/yr, although significant, represents variation across different operations and technology levels reported in the literature, rather than year-to-year variability within a single well-managed facility.

Scenario C – Operating Expenditure (OPEX): Scenario C applies upward shocks of 0.5σ and 0.67σ to the OPEX rate, increasing it from $14.22/ft²/yr to $20.99/ft²/yr and $23.29/ft²/yr, respectively. These shocks may be conceived of as operating cost components increasing beyond the assumed average. Under the 0.5σ shock, which has a 30.9% probability of occurrence under the normal distribution, the NPV becomes negative at $147,606, the IRR declines to 6.86% (below the 8.0% WACC), and the payback period extends to 10.71 years. The negative NPV and IRR indicate that the project fails to recover its cost of capital. As expected, the 0.67σ shock further deteriorates the NPV to -$438,072 and the IRR decreases to 4.41%, which is approximately half the required WACC. The further decline in NPV and IRR and the payback period extends to 12.77 years confirms increasing non-viability. The severity of these outcomes is attributable to the exceptionally wide standard deviation of operating costs ($13.53/ft²/yr), reflecting significant heterogeneity in reported OPEX across greenhouse operations of varying scale, technology intensity, energy cost environments, and labor market conditions. This distributional width implies that a 0.5σ adverse OPEX shock results in a near-doubling of the base case operating cost rate, which is a structurally plausible outcome for a new entrant operating in a high-energy-cost region such as southwest Kansas.

Scenario D – Capital Expenditure (CAPEX): Scenario D introduces upward shocks of 0.5σ and 0.67σ to the CAPEX rate, increasing it from $98.20/ft² to $126.98/ft² and $136.76/ft², respectively. These shocks may be conceived of as cost overruns in the construction of the greenhouse or in the acquisition of equipment. With a 0.5σ shock, NPV declines to $203,120, representing a reduction of $503,585 or 71.3% below the base case. The IRR remains above the WACC threshold, and the BCR exceeds unity, demonstrating continued value generation for investors under moderately increased capital costs. At the 0.67σ shock, NPV decreases further to $31,888, and the IRR drops to 8.17%, marginally above the 8.0% WACC together with a payback period of 9.97 years, reflects marginal but technically viable outcomes.

Figure 4.3 Tornado Chart of the One-Way Sensitivity Analysis ±0.50, 0.67 Standard Deviation (σ)



4.6.2 Two-Way Sensitivity Analysis

Table 4.13 summarizes the outcomes of six two-way sensitivity scenarios (Scenarios E through J), each involving simultaneous adverse shocks of 0.5σ and 0.67σ to two uncertain variables, with all other parameters maintained at their base scenario values. The shock magnitudes correspond to the 30.9th and 25th percentiles of the assumed normal distributions, respectively. Consequently, the probability of both variables simultaneously reaching or exceeding these adverse levels is approximately 9.5% for the 0.5σ scenario (0.309 × 0.309) and

6.25% for the 0.67σ scenario (0.25 × 0.25), assuming independence between variables. These joint probabilities are significant; under the independence assumption, a one-in-sixteen likelihood of the 0.67σ joint scenario occurring in any given year.

Table 4.13. Two-Way Sensitivity Analysis Results (±0.5 and ±0.67σ Simultaneous Shocks)

Scenario	Shock Applied	NPV ($) 0.5σ	ΔNPV ($) 0.5σ	NPV ($) 0.67σ	ΔNPV ($) 0.67σ
E	Price −nσ & Yield −nσ	($594,791)	($1,301,496)	($1,003,157)	($1,709,862)
F	Price −nσ & OPEX +nσ	($1,217,545)	($1,924,250)	($1,874,821)	($2,581,526)
G	Price −nσ & CAPEX +nσ	($866,819)	($1,573,524)	($1,404,862)	($2,111,567)
H	Yield −nσ & OPEX +nσ	($460,649)	($1,167,354)	($857,951)	($1,564,656)
I	Yield −nσ & CAPEX +nσ	($109,924)	($816,629)	($387,992)	($1,094,697)
J	OPEX +nσ & CAPEX +nσ	($651,191)	($1,357,896)	($1,112,889)	($1,819,594)

The two-way sensitivity analysis demonstrates that no pairing of simultaneous one-standard-deviation adverse shocks preserves project viability. The critical implication for investment decision-making is that the base case NPV of $706,705, while positive, represents a narrow buffer that is eliminated when any two value drivers deteriorate concurrently. Therefore, risk mitigation strategies must address multiple value drivers simultaneously rather than focusing on any single variable in isolation.

Scenario F (Price and OPEX) produces the most severe outcome, with NPVs of −$1,217,545 and −$1,874,821 at the 0.5σ and 0.67σ levels, respectively. In this scenario, lower prices and higher operating costs jointly eliminate the positive gross margin. Scenario G (Price and CAPEX) is the second most severe, yielding NPVs of −$866,819 and −$1,404,862, which highlights the amplifying effect of a construction and/or equipment procurement cost overruns. Scenario E (Price and Yield) results in NPVs of −$594,791 and −$1,003,157, indicating a simultaneous decline in both price and yield components of revenue. From the one-way sensitivity analysis, this result was already obvious.

Scenario J (OPEX and CAPEX) yields NPVs of −$651,191 and −$1,112,889, demonstrating that cost overruns alone can undermine project viability even when revenues remain at base case levels. Scenario H (Yield and OPEX) results in NPVs of −$460,649 and −$857,951, underscoring the enterprise's vulnerability to concurrent production shortfalls and cost escalation. Scenario I (Yield and CAPEX) is the least severe, with NPVs of −$109,924 and −$387,992, indicating that the yield-CAPEX combination is the most recoverable adverse scenario and is most amenable to mitigation through operational efficiency and capital cost containment.

4.6.3 Sensitivity of Net Present Value to the WACC

The preceding sensitivity scenarios quantify the impact of adverse operational shocks on investment viability. An equally important aspect of sensitivity analysis involves the discount rate applied to future cash flows. The weighted average cost of capital (WACC) incorporates both the cost of debt and the required return on equity, making it sensitive to the perceived risk associated with the investment. Since greenhouse tomato production represents a novel technology and an unfamiliar production system for producers in southwest Kansas, prospective investors and agricultural lenders may assign a risk premium above the 8.0% base case rate. At the upper bound, a WACC of 14.0% frames the greenhouse enterprise as a technology investment rather than a conventional agricultural project, which is appropriate given the lack of regional precedent and the capital-intensive nature of the system. Table 4.14 summarizes the sensitivity of the base case net present value (NPV) to WACC assumptions of 8%, 10%, 12%, and 14%.

Table 4.14. Sensitivity of Net Present Value to Alternative WACC Assumptions

WACC Assumption	Net Present Value (NPV)	Change from Base Case ($)	Change from Base Case (%)
8% (Base Case)	**$706,705**	—	—
10%	$368,785	($337,920)	(47.8%)
12%	$100,617	($606,088)	(85.8%)
14%	($114,973)	($821,678)	N/A — NPV < 0

Table 4.14 demonstrates a consistent decline in net present value (NPV) as the discount rate increases, illustrating the greater opportunity cost imposed on a fixed stream of future cash flows. At the base case weighted average cost of capital (WACC) of 8.0%, the NPV of $706,705 supports the project's financial feasibility under standard agricultural borrowing conditions. When the discount rate rises to 10.0%, the NPV decreases to $368,785, representing a reduction of $337,920, or 47.8% from the base case, but remains significantly positive. This outcome suggests that the enterprise continues to generate substantial economic value even when investors require a moderate risk premium. At a 12.0% discount rate, the NPV drops to $100,617, an 85.8% decrease from the base case. Although the project remains technically viable at this rate, the narrow positive margin indicates proximity to the threshold of financial indifference. At 14.0%, the NPV becomes negative at ($114,973), demonstrating that the project does not provide adequate returns for investors applying a technology-sector risk premium.

A principal finding from this analysis is that the internal rate of return (IRR) of 12.88%, which remains constant regardless of the discount rate, establishes the maximum WACC at which the project is financially sustainable. Investors or lenders requiring returns above 12.88% would be unlikely to finance the enterprise, as the projected cash flows would not meet their cost of capital. In contrast, investors with required returns at or below 12.88% would observe a positive NPV. This outcome indicates that the greenhouse enterprise is financeable at agricultural lending rates and at moderately increased risk premiums, but not at rates typical of technology-sector investments. Implementing risk-mitigation strategies, such as secured offtake agreements, government-backed loan guarantees for innovative agricultural projects, or cooperative ownership models that distribute equity requirements, could reduce the effective WACC and broaden the pool of potential investors.

4.7 Monte Carlo Simulation

The Monte Carlo simulation advances the deterministic sensitivity analysis by simultaneously sampling all four uncertain input variables from their empirical normal distributions over 10,000 iterations. This process generates the joint probability distribution of net present value (NPV) outcomes. In contrast to one-way and two-way sensitivity analyses, which apply fixed discrete shocks to individual variables, the Monte Carlo framework captures the entire spectrum of possible input combinations, including favorable, unfavorable, and mixed scenarios, each weighted by its probability under the specified distributional assumptions. Tables 4.15, 4.16, and 4.17 summarize the simulation parameters, the resulting NPV distribution, and the viability outcomes.

Table 4.15. Monte Carlo Simulation Parameters

Statistic	Value	Coefficient of Variation
Iterations (N)	10,000	
Price ($/lb)	Normal (μ=\$2.31, σ=\$1.21)	0.524
Yield (lb/ft²/yr)	Normal (μ=15.44, σ=2.36)	0.153
OPEX ($/ft²/yr)	Normal (μ=\$14.22, σ=\$13.53)	0.952
CAPEX ($/ft²)	Normal (μ=\$98.20, σ=\$57.55)	0.586

Table 4.16: Summary Statistics from Monte Carlo Simulations

Statistics	Estimated Value
Mean NPV	$635,940
Median NPV	$607,990
Std Deviation (σ_NPV)	$2,858,167
PERCENTILES (VaR)	
5th Pct — VaR_{95}	($4,030,217)
10th Pct	($3,037,207)
25th Pct (Q1)	($1,329,889)
75th Pct (Q3)	$2,555,334
90th Pct	$4,330,833
95th Pct	$5,302,100
Minimum NPV	($9,479,884)
Maximum NPV	$11,885,301

Table 4.17: Summary Statistics of Viability Outcomes

Viability Outcomes	Summary Estimate
P(NPV ≥ $0)	58%
P(NPV < $0)	42%
Mean NPV | Viable (i.e., NPV ≥ 0)	$2,558,322
Mean NPV | Non-viable (NPV < 0)	($2,041,777)

The mean NPV from the 10,000 simulations of the Monte Carlo was $635,940, indicating that the project generates positive expected value under the assumed input distributions and randomly generated risk conditions for all the critical variables. However, this average NPV is lower than the deterministic base case NPV of $706,705, highlighting the asymmetric downside risk that arises when all four variables vary simultaneously. The median NPV of $607,990 is lower the mean, indicating that the resulting NPV is positively skewed, with a long tail of high values pulling the mean upwards while the median remains centrally located. In simple terms, the median is not influenced by outliers, but the mean is. This is confirmed by the mean of positive NPV being higher than the mean of negative NPV outcomes. The standard deviation of $2,858,167 reflects the wide dispersion of outcomes, underscoring the considerable uncertainty inherent in the input distributions, particularly OPEX, which has the highest coefficient of variation at 0.952.

The probability of investment viability, defined as P(NPV ≥ 0), is 58%, indicating that slightly more than half of simulated iterations yield a positive net present value. The complementary probability of non-viability is 42%, demonstrating that in about 4.2 cases out of 10, the plausible outcome combinations of price, yield, OPEX and CAPEX produced results that were below the investment cost. The relatively low probability of investment viability indicates the riskiness of the project.

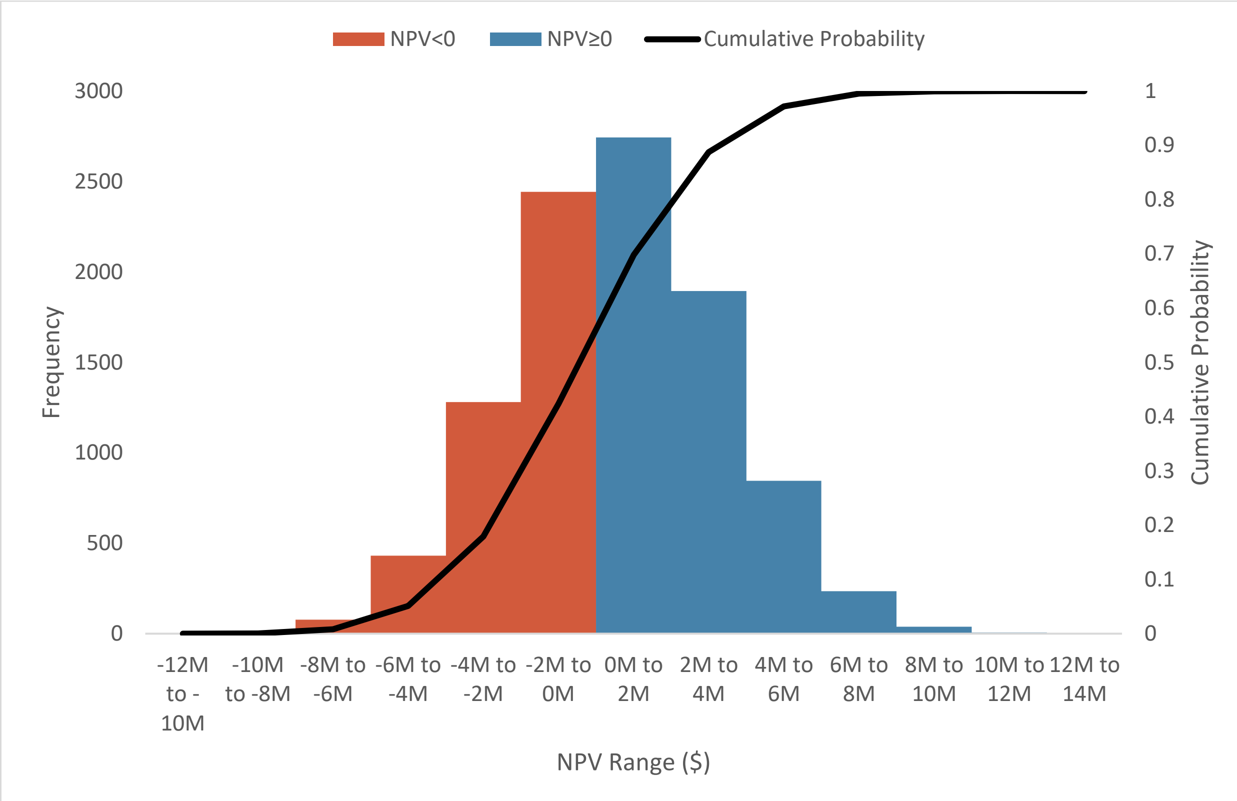
Thus, while the deterministic model confirms feasibility under expected-value assumptions, the stochastic model shows that the project's viability is not guaranteed and that a significant proportion of plausible real-world outcomes would result in financial losses. Among the 5,821 viable simulations, the mean NPV is $2,558,322; among the 4,179 non-viable simulations, the mean NPV is ($2,041,777). In addition to central tendency measures, the standard deviation of simulated NPV serves as a key indicator of overall project risk. Larger standard deviation values reflect greater dispersion in potential financial outcomes. At the baseline 8% discount rate, the standard deviation of NPV is $2,858,167, which demonstrates substantial variability in outcomes due to uncertainties in price, yield, OPEX, and CAPEX. Therefore, although the mean NPV is positive, the project remains exposed to significant downside risk, underscoring the necessity of risk-adjusted evaluation.

The Value at Risk (VaR_{95}) at the 95% confidence level or the 5^{th} percentile yields an NPV of negative $4,03 million, which indicates the maximum loss expected in the worst 5% of simulated outcomes. At the 90% confidence level or 10^{th} percentile, the VaR was negative $3.04 million – the maximum expected loss in the worst 10% of simulated outcomes. The expected

NPV at the 25th percentile was negative $1,33 million, indicating that the worst 25% of outcomes potentially destroys more than $1,33 million of value relative to the opportunity cost of capital. The pull of the upper tail is the project's redemption. At the 75th percentile, the VaR was approximately $2.56 million while the VaR at the 90th percentile was$4.33 million. Finally, the 95th percentile produced a VaR in excess of $5.30 million. The simulated NPV ranged from was about negative $9.5 million to $11.89 million. These results were driven essentially by the implied uncertainty of price and OPEX and not as much by yield and CAPEX.

Overall, the Monte Carlo results suggest that the greenhouse tomato enterprise is financially viable, with a positive mean NPV, a majority probability of positive outcomes, and substantial upside potential under favorable market conditions. However, the enterprise also entails significant downside risk. The 42% probability of non-viability warrant careful consideration by prospective investors, agricultural lenders, and policy stakeholders assessing the enterprise as an adaptation strategy for southwest Kansas farms. These findings reinforce the sensitivity analysis conclusions: price risk is the primary determinant of viability, and revenue stabilization mechanisms, such as forward pricing arrangements, direct retail relationships, and premium market positioning, constitute the highest-priority risk mitigation objectives for prospective operators.

Figure 4.4. Monte Carlo Simulation Results



4.7.1 Monte Carlo Results Under Alternative WACC Assumptions

The preceding stochastic analysis characterizes the distribution of NPV outcomes at the base case weighted average cost of capital (WACC) of 8.0%. To complement the deterministic WACC sensitivity analysis in Section 4.6.3 and to quantify the interaction between investor risk appetite and the full distribution of simulated outcomes, the Monte Carlo simulation was repeated at discount rates of 10%, 12%, and 14%. Table 4.18 provides a summary of the most policy-relevant distributional statistics for all four WACC scenarios.

Table 4.18. Monte Carlo Simulation Results Under Alternative WACC Assumptions (N = 10,000 Iterations)

Metric	8%	10%	12%	14%
NPV Distribution				
Mean NPV	$635,940	$233,226	$23,035	($209,238)
Median NPV	$607,990	$199,027	($3,770)	($234,224)
Std. Deviation	$2,858,167	$2,480,642	$2,172,746	$1,972,277
Percentiles and Value at Risk				
VaR_{h5} (5th Percentile)	($4,030,217)	($3,785,562)	($3,543,158)	($3,424,021)
25th Percentile (Q1)	($1,329,889)	($1,445,096)	($1,452,972)	($1,544,110)
75th Percentile (Q3)	$2,555,334	$1,861,680	$1,509,362	$1,123,262
95th Percentile	$5,302,100	$4,373,249	$3,584,414	$3,051,378
Viability Outcomes				
P(NPV ≥ 0)	58%	53%	50%	45%
P(NPV < 0)	42%	47%	50%	55%
Mean NPV | Viable	$2,558,322	$2,070,226	$1,765,932	$1,513,908
Mean NPV | Non-Viable	($2,041,777)	($1,872,682)	($1,712,905)	($1,645,508)

NPV Distribution: Increasing WACC has a negative effect on NPV. The simulations provided evidence of the extent of the negative impact. The mean simulated NPV declines from $635,940 at an 8.0% discount rate to $233,226 at 10.0%, $23,035 at 12.0%, and ($209,238) at 14.0%. That is, a 25% increase in WACC resulted in a 66.33% decline in NPV, showing the significant marginal responsiveness of the project's performance to WACC risks. It also shows that the right tail's ability to compensate for the VaR disappears rapidly under WACC risks. At 14% WACC, the investment viability was 45%.

The standard deviation of simulated NPV declines as the WACC increases, from $2,858,167 at 8.0% to $1,972,277 at 14.0%. This pattern results from the mathematical compression of future cash flows at higher discount rates, which diminishes the influence of distant, high-variance outcomes on total NPV variability. Although the reduction in spread may appear to indicate lower risk at higher WACCs, this interpretation is misleading. The underlying business risk, driven by price and operating expenditure (OPEX) uncertainty, remains constant across WACC scenarios. The narrowing of the distribution reflects the reduced significance of future outcomes rather than an actual improvement in project stability.

Value at Risk (VaR) and Percentile Analysis: The Value at Risk at the 95% confidence level (VaR_{95}), which represents the maximum loss expected in the worst 5% of simulated outcomes, declines modestly in absolute terms as the WACC increases, from ($4,030,217) at 8.0% to ($3,424,021) at 14.0%. The 25th percentile, indicating the NPV outcome below which one in four simulated scenarios falls, remains substantially negative across all WACC scenarios, ranging from ($1,329,889) at 8.0% to ($1,544,110) at 14.0%. This persistent negativity suggests that the lower quartile of simulated outcomes implies capital destruction regardless of the discount rate, and that downside exposure is a structural characteristic of the investment driven by input uncertainty rather than the cost of capital. The 75th percentile decreases significantly from $2,555,334 at 8.0% to $1,123,262 at 14.0%, illustrating the erosion of upside potential as the discount rate increases. The asymmetry between downside and upside outcomes narrows as the WACC rises, indicating that higher discount rates disproportionately compress the favorable tail of the NPV distribution.

Probability of Investment Viability: The probability of investment viability, defined as $P(NPV \geq 0)$, decreases from 58% at 8.0% to 53% at 10.0%, 50% at 12.0%, and 45% at 14.0%. The 50% viability probability at 12.0% aligns with the near-zero mean and median NPV at that discount rate, confirming that the enterprise is at the threshold of expected feasibility when a high risk premium is applied. At 14.0%, with a viability probability of 45%, fewer than half of simulated scenarios yield a positive NPV. This outcome indicates that the project is statistically more likely to destroy capital than to create it when evaluated at a technology-level discount rate. The conditional mean NPV among viable outcomes declines from $2,558,322 at 8.0% to $1,513,908 at 14.0%, while the conditional mean NPV among non-viable outcomes improves modestly from ($2,041,777) to ($1,645,508). This reflects the compression of both tails of the distribution at higher discount rates. Collectively, these results demonstrate that the enterprise's stochastic viability is sensitive to the cost of capital, and that securing financing at or near conventional agricultural lending rates is essential for the enterprise to achieve majority-probability feasibility.

4.8 Comparative Analysis: Traditional Farming vs. Greenhouse Tomato Production

The majority of this study has focused on the economic feasibility and riskiness of producing tomatoes under CEA conditions with the objective of preserving farm net income and reducing withdrawals from the Ogallala Aquifer. In Section 4.1, the financial and water use profiles of a typical southwest Kansas irrigated grain farm were established, while Sections 4.2 through 4.7 developed and stress-tested the economic feasibility of a hydroponic greenhouse tomato operation. The remaining question is this: Does the greenhouse tomato enterprise sustain or improve farm income while substantially reducing withdrawals from the Ogallala Aquifer?

The comparison does not involve equivalent scales of production. The traditional farm operates across 1,467 acres, whereas the greenhouse occupies a single less than one acre (17,502 ft^2, approximately 0.40 acres). The traditional farm uses almost 1,300 acre-feet of Ogallala groundwater annually while the greenhouse production uses 1.48 acre-feet per year. This leads us to assessing the water productivity, measured as net farm income per acre-foot, rather than total production volume.

The traditional farm achieves a five-year average net farm income of $147,853, based on KFMA southwest Kansas data from 2020 to 2024 and scaled to 1,467.21 acres. This benchmark represents the realized net farm income for the typical farm in the region during that period and serves as the income-equivalence target established in Chapter 3. The greenhouse enterprise was specifically designed to match this net farm income benchmark. With a facility size of 17,502 ft^2, it generates a Year 1 net income of $147,853, thereby confirming that the income-equivalence condition is met. This equivalence is intentional, as the 17,502 ft^2 facility size was determined endogenously from the income-equivalence condition in Chapter 3. As a result, the greenhouse is sized to deliver the same financial outcome as a typical farmer under base-case assumptions of price and yield.

4.8.1 Water Use and Water Productivity

The primary empirical finding of this analysis is the significant disparity in water use between the two enterprises. The 1,467.21-acre traditional farm withdraws 1,289.1 acre-feet of Ogallala groundwater annually to support its four-crop irrigated portfolio. In contrast, the greenhouse's annual water consumption, calculated from its gross tomato output of 229,632 lb (104,159.2 kg) at a rate of 17.5 liters per kilogram (Van Kooten et al., 2008) , totals 1,822,787 liters, or 1.48 acre-feet per year. This implies a reduction of 1,287.6 acre-feet, or 99.9%, in annual groundwater withdrawals compared to the traditional farm..

A comparison of water productivity illustrates the magnitude of this difference. The traditional farm generates $115 in net farm income per acre-foot of Ogallala water withdrawn, based on the Kansas Farm Management Association (KFMA) five-year average benchmark of $147,853 applied to 1,289.1 acre-feet. In contrast, the greenhouse generates $99,901 in net farm income per acre-foot. Thus, each acre-foot of groundwater used in the greenhouse yields approximately 872 times more net farm income than the same volume applied to the traditional crop mix. Importantly, both enterprises achieve the same absolute net farm income of $147,853, confirming that the income-equivalence condition is met.

The foregoing results present significant policy implications. Conservation efforts aimed at reducing water use within existing irrigated grain systems may slow aquifer depletion but do not alter the underlying economic reality: Each acre-foot of Ogallala water applied to commodity grains currently incurs greater economic costs than the net income it generates. The greenhouse model reframes the issue by demonstrating that the prevailing crop-water combination in southwest Kansas results in negative returns per unit of water consumed. Replacing this system with a high-value enterprise characterized by substantially lower water intensity addresses both income and aquifer sustainability challenges concurrently.

Table 4.19. Comparative Summary: Typical Farmer vs. Greenhouse Tomato Enterprise

Metric	Typical Farmer	Greenhouse (Base Case)
Financial Performance		
Annual Net Farm Income ($)	$147,853	$147,853
Water Use and Productivity		
Total Annual Water Use (ac-ft/yr)	1,289.1	1.48
NFI per Ac-Ft ($/ac-ft)	$115	$99,900.68
Water Saved vs. Traditional (ac-ft/yr)	-	1,287.6
Water Reduction (%)	-	99.9%
Land and Scale		
Production Area	1,467.21 acres	17,502 ft² (~0.40 ac)

4.8.2 Limitations

Several important qualifications must be considered in the foregoing comparison. First, the greenhouse base case net present value (NPV) of $ 706,705 reflects the expected-value outcome under baseline assumptions. The Monte Carlo simulation indicates that the probability of NPV being greater than or equal to zero is 58%, implying that 42% of simulated scenarios result in a financially non-viable project when accounting for the joint distribution of all four uncertain inputs. In contrast, the traditional farm represents a familiar and established production system for operators in southwest Kansas, despite its structural unprofitability. Although it has similar loss potential as the greenhouse enterprise, there is a certain familiarity with its risks, a familiarity that is absent from the greenhouse investment.

Second, the regional market implications of widespread greenhouse adoption are not modeled. If numerous farms simultaneously transition to greenhouse tomato production, increased local supply could lower wholesale prices and diminish the revenue advantage observed in the base case. Consequently, market access and supply chain development are critical infrastructures that must be developed to facilitate the effective scaling of this project to create a viable industry in southwest Kansas. Developing this infrastructure could reduce price and OPX uncertainty, provide lower CAPEX costs as builders and equipment suppliers seize the opportunity to increase their own markets and sales revenues.

Third, the 2020–2024 KFMA reference period includes years characterized by significant drought in southwest Kansas, with multi-year drought conditions that substantially reduced crop yields and net farm incomes throughout the region. However, it also presented a year of uncharacteristically very high net farm income (nearly $320,000 in 2021). Thus, while the benchmarked net farm income might seem like a lower bound of income possibilities in the region, the statistical foundation of the modelling process would indicate that the benchmark income is within the realm of possibility. This argument notwithstanding, since the benchmark income determines the size of the greenhouse, it becomes a moot point since any farmer might establish their benchmark or desired income necessary to sustain their lifestyle and proceed to build it. The solution will be scalar from the results emanating from this research, ceteris paribus.

Fourth, unlike the grain crops which have low storability cost, fresh tomatoes are highly perishable. This underscores probably the biggest strategic consideration in building a greenhouse enterprise in southwest Kansas. The transportation infrastructure must be developed quickly to ensure rapid access to markets in Denver and San Francisco in the West, Denver and Houston in the southeast, and Chicago and New York City in the northeast. The critical reality is that the project does not present any unique characteristics of the tomatoes produced in southwest Kansas to give them any special competitive advantage in these markets. Which means, products from southwest Kansas will be competing against the imports from Mexico and elsewhere.

Fifth, all cost and revenue parameters are based on global and national controlled environment agriculture (CEA) literature averages, rather than primary data from southwest Kansas or similar U.S. Great Plains regions. The lack of regionally calibrated input distributions, particularly for capital expenditures (CAPEX), operating expenditures (OPEX), and wholesale prices, results in a financial model that represents the central tendency of a diverse global dataset instead of the specific cost and revenue conditions encountered by operators in southwest Kansas. This dependence on literature averages introduces parameter uncertainty that exceeds what is reflected in the standard deviation estimates used in the sensitivity and Monte Carlo analyses. Consequently, the model may under- or overestimate key cost components if regional conditions systematically differ from the global mean. This limitation is the primary motivation for the primary data collection recommendation in Section 5.2.

Potential investors, therefore, need to consider leveraging the existing transportation infrastructure and technologies that enable the long-distance shipping of tomatoes. They need to explore strategic alliance opportunities with downstream supply chain actors to minimize cost and increase market competitiveness. There is also value in considering the development of a variety that addresses recognized pain points in the current market and consider the trajectory of future consumer preferences. It also makes strategic sense to consider increase operational scale enough to facilitate value addition in southwest Kansas, and in the process reducing shipment costs and improving storability of the product. For example, producing sun-dried tomatoes from the fresh product by leveraging the regions solar and wind resources would cut down on volume shipped and capture some of the original water used in production for recycling.

These issues have not been addressed in this study. However, they are all very critical in the foregoing results being realized. Therefore, this work may be considered the preliminary exploration of the technical and economic feasibility of using novel technology and production system to conserve the Ogallala Aquifer without sacrificing farm income. The future work on exploring the strategic infrastructure and other investments needed to build this novel and innovative solution to an age-old problem that seems to be defying a solution must first be considered.

Chapter 5 - Conclusion and Recommendations

5.1 Conclusions

The foregoing analyses have demonstrated that a high-technology hydroponic greenhouse tomato enterprise is both technically and economically feasible in contributing to addressing the Ogallala Aquifer challenge confronting Kansas and other regions in the High Plains. The specified physical parameters, including 17,502 ft^2 Dutch-style high-wire system with supplemental LED lighting, precision fertigation, and climate control, are consistent with prevailing commercial standards in North American and Western European greenhouse operations. The baseline yield of 15.44 pounds per square foot per year is conservative relative to the upper range of published commercial yields and is achievable with effective management. Water consumption at 17.5 liters per kilogram of output is within documented ranges for recirculating hydroponic systems. Moreover, operational challenges specific to southwest Kansas, such as high energy costs, limited labor availability, distance from major population centers, and the absence of an established regional greenhouse supply chain, are significant but not prohibitive. These challenges resemble those faced by early adopters of greenhouse technology in other agricultural regions and can be addressed through infrastructure investment, cooperative organization, and targeted policy support.

The base case analysis indicates economic feasibility under expected-value assumptions. The greenhouse enterprise generates a positive net present value (NPV), an internal rate of return (IRR) that exceeds the cost of capital. According to these metrics, the enterprise satisfies standard investment appraisal thresholds. However, this feasibility is conditional. Monte Carlo simulation results indicate that 42% of plausible real-world scenarios result in non-viability. This represents a substantive risk, reflecting genuine uncertainty regarding wholesale tomato prices, which are the primary determinant of outcome variability. An investor who enters this enterprise without a secured price pathway, offtake contract, or access to premium markets is effectively making a speculative investment in a volatile commodity. Therefore, the conclusion is not that the greenhouse enterprise is unconditionally feasible, but rather that feasibility depends on conditions that can be actively managed. Securing price certainty and controlling operating costs are the primary factors that determine whether the enterprise achieves its potential.

The water conservation benefits of the greenhouse enterprise are evident and are independent of economic outcomes. Regardless of profitability, each acre of greenhouse tomato production that replaces an acre of irrigated grain production reduces annual Ogallala Aquifer withdrawals by approximately 1,287.6 acre-feet (99.9% less water). According to the 2022 USDA Census of Agriculture, the southwest Kansas district encompasses 5,205 farms across 13 counties, with individual farm sizes averaging between 1,124 and 2,122 acres (The University of Kansas, 2025) establishing the full scale of potential adoption in the region. Adoption by 50 farms would result in annual savings of approximately 63,880 acre-feet.

The income-equivalence result presented in this thesis establishes a conservative lower bound for total farm income following conversion. The greenhouse facility occupies only 0.40 acres, leaving approximately 1,466 acres of the typical farm's cropland unaccounted for in the financial model. In practice, these remaining acres would continue to generate income, either through dryland crop production such as winter wheat, triticale, grain sorghum, or through annual rental payments under a federal conservation program such as the Conservation Reserve Program (CRP). In either scenario, total farm income after conversion would surpass the $147,853 greenhouse income-equivalence benchmark established in this analysis. The greenhouse enterprise should not be considered a replacement for the entire farm operation.

Instead, it serves as an income anchor that, when combined with the productive or conservation use of the remaining acres, could render the converting farm substantially more financially resilient than the traditional irrigated grain baseline.

The risk profiles of the two production systems differ substantially in both structure and magnitude. For the traditional irrigated grain farm, the standard deviation of net farm income during the 2020–2024 KFMA period was $72,210, resulting in a coefficient of variation (CV) of 48.8%. This value reflects considerable year-to-year income volatility, primarily attributable to fluctuations in commodity prices and drought cycles. In contrast, the greenhouse enterprise, as modeled using Monte Carlo simulation, exhibits a standard deviation of $2,858,167 in simulated net present value (NPV), with a mean of $635,940. Although these measures are not directly comparable, as one reflects realized annual income variability and the other represents uncertainty in a 20-year present value, both systems display high outcome variability relative to their respective means. The primary distinction lies in the sources of risk: traditional irrigated grain farming is subject to largely uncontrollable weather and commodity market fluctuations, whereas the greenhouse enterprise faces uncertainty related to technology adoption and wholesale tomato price risk. These latter risks can be partially mitigated through offtake contracts, premium market positioning, and effective operational management.

An important systemic factor not addressed by the financial model is the potential downstream impact on the cattle feeding and dairy industries in southwest Kansas. This region is among the most livestock-intensive in the United States, with counties such as Haskell, Gray, and Finney consistently ranking as leading agricultural producers in Kansas, primarily due to cattle feeding and dairy operations (The University of Kansas, 2025). These industries depend heavily on locally produced feed grains, especially irrigated corn and grain sorghum, provided by the current cropping system. A large-scale transition of irrigated grain acreage to greenhouse tomato production could reduce the local feed supply, potentially raising feed costs for concentrated animal feeding operations or increasing reliance on imported grain. Conversely, decreased competition for irrigation water from farms converted to greenhouse production could benefit livestock producers who use the same aquifer. The net effect on the regional cattle and dairy economy remains uncertain and will depend on the scale and pace of adoption, underscoring the need for future integrated regional economic analysis.

5.2 Recommendations

Several directions for future research emerge from the findings and limitations of this study. First, conducting primary data collection on existing greenhouse tomato operations in the central United States would improve the accuracy of cost and revenue parameters in the financial model. Surveys of operators in Kansas, Colorado, Nebraska, and Oklahoma, which share similar climate, energy costs, and labor market characteristics with southwest Kansas, would yield regionally calibrated distributions for capital expenditures (CAPEX), operating expenditures (OPEX), and wholesale prices that are more representative than the global literature averages currently used.

Second, empirical investigation of the adoption decision is warranted. Implementing a survey or choice experiment targeting farm operators in southwest Kansas would help identify capital access thresholds, risk tolerance parameters, market access requirements, and non-pecuniary barriers that constrain adoption. Such information is essential for designing effective policy interventions.

Third, modeling the aggregate hydrological effects of enterprise substitution at scale using existing High Plains aquifer simulation frameworks is necessary. The water savings projections presented in Table 14.19 are currently calculated as linear aggregates of individual farm-level reductions. Translating these reductions into aquifer-level stabilization trajectories and quantifying their interaction with regional climate change projections would provide a more comprehensive assessment of conservation benefits and reinforce the policy rationale for public investment in enterprise substitution programs.

Fourth, an in-depth comparative case study of established greenhouse tomato production regions, particularly Almería, Spain, could provide valuable operational and institutional benchmarks for southwest Kansas. Almería represents the world's largest greenhouse vegetable production cluster and operates in an arid, water-scarce environment with a strong emphasis on exports. The region's experience demonstrates that large-scale greenhouse adoption in resource-limited areas is achievable within a generation when there is coordinated investment in infrastructure, robust cooperative organizations, and supportive trade policies. By systematically documenting the institutional, financial, and logistical steps that enabled Almería's transition from dryland farming to a globally competitive greenhouse sector, researchers can develop a practical guide for policymakers and agricultural development practitioners seeking to facilitate a similar transformation in the U.S. High Plains.

Fifth, the policy framework governing land use transitions and water rights disposition requires explicit consideration before large-scale implementation of enterprise substitution programs. When a farm operator converts from 1,467 irrigated acres to a 0.40-acre greenhouse facility, the remaining cropland typically could follow these subjected trajectories: conversion to dryland production, such as winter wheat or grain sorghum, given the regional agroclimate, or enrollment in a federal conservation program like the Conservation Reserve Program (CRP).

Each pathway has distinct implications for regional farm income, groundwater withdrawals, and commodity supply.

Finally, the business development dimension of the project must be considered thoroughly. The project's success will be greatly enhanced if farmers, communities, processors, distributors, retailers, and governments could come together with private investors to explore who to build a brand new industry in southwest Kansas to provide scale and reach for the greenhouse tomato industry. There are lessons from Southern Spain and elsewhere that need to be studied and adapted for superior performance.

5.3 Policy Implications and Practical Considerations

The findings of this research have practical implications for two primary groups: policymakers responsible for agricultural development, water governance, and rural economic programs in southwest Kansas, and farm operators assessing the feasibility of enterprise substitution within their operations.

Policy Implications: Water right retirement and buyout programs should be designed to account for enterprise substitution. When farm operators transition from irrigated grain to greenhouse production, the Ogallala water rights associated with 1,467 acres of irrigated cropland become unused. In the absence of a formal mechanism for retiring or transferring these rights, water savings are unlikely to be preserved at the aquifer level. Establishing a voluntary buyout program, modeled after conservation easement mechanisms used for farmland, would help ensure that enterprise substitution leads to enduring aquifer conservation.

Access to capital is the primary constraint on adoption. The initial capital requirement of approximately \$1.72 million for the 17,502 ft^2 facility modeled in this study exceeds the financial capacity of most individual farm operations without external financing. Loan guarantee programs, USDA Farm Service Agency beginning farmer and rancher loans, and state-level agricultural innovation grants focused on controlled environment agriculture could substantially reduce the effective cost of capital and broaden the pool of potential adopters beyond well-capitalized operators.

Investment in market infrastructure is critical for regional-scale adoption. Fresh tomatoes are highly perishable and require refrigerated logistics, proximity to buyers, and established distribution networks, all of which are currently non-existent in southwest Kansas.

Positioning greenhouse development as an import substitution initiative can strengthen the policy rationale for public investment. As documented in Chapter 2, imports account for approximately 88 percent of the U.S. domestic greenhouse tomato supply, with a total import value of $3.28 billion in 2023 (Weber & Davis, 2024, World Bank WITS, 2023). Framing southwest Kansas greenhouse development as a domestic food security and import substitution initiative, rather than solely a water conservation program, expands the coalition of potential policy supporters and reinforces the case for federal investment through agricultural trade, rural development, and food security funding streams.

Implications for Farm Operators: Securing a market prior to construction is critical. Unlike commodity grain, which can be sold into established exchange markets at any time, fresh tomatoes require immediate sale after harvest. Operators who construct a greenhouse without an identified buyer, such as a wholesale distributor, regional grocery chain, food service operator, or direct retail arrangement, face substantial income risk from the outset. Offtake agreements, forward contracts, or confirmed relationships with institutional buyers should be established before committing capital.

Tomato variety selection directly affects both market channel and achievable price. Market data indicate that specialty formats, such as grape, cherry, and vine-ripe tomatoes, command retail prices ranging from $0.99 to over $3.99 per pound (Simonne et al., 2006), while commodity round tomatoes face intense price competition from Mexican imports. Operators targeting wholesale channels should select varieties that correspond with demonstrated consumer demand for greenhouse-specific specialty formats, as these offer higher price premiums and stronger domestic market positioning compared to imported field tomatoes.

Effective management of operating costs, particularly energy expenses, is equally important as price realization. Sensitivity and Monte Carlo analyses confirm that operating expense shocks are among the most significant threats to project viability. Energy costs in southwest Kansas are substantial, and year-round heating and cooling of a controlled environment facility represent major fixed cost exposures. Operators should evaluate energy procurement strategies, such as fixed-rate utility contracts, cooperative purchasing arrangements, or on-site renewable energy installation, during the pre-investment planning process or consider developing their own energy from the abundant wind and solar resources in the region.

Cooperative or cluster adoption can reduce individual risk. A single greenhouse operator in southwest Kansas bears the full burden of market development, logistics coordination, and supply chain establishment. A group of operators adopting jointly can share the fixed costs of refrigerated transport, negotiate collectively with regional buyers, and develop a recognizable regional brand identity.

The financial model presented in this thesis assumes a well-managed, fully operational facility from the first year. In practice, new operators should anticipate a learning curve of one to two production cycles before achieving baseline yields and cost structures.

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Arid-Land Agricultural Research Center, Maricopa, AZ 85138, USA, 5. Dept. of ICT and Natural Sciences, Faculty of Information Technology and Electrical Engineering, Norwegian University of Science and Technology(NTNU), Larsg鋕dsveien 2, NO-6009 談esund, Norway, 6. Leibniz Institute for Agricultural Engineering and Bioeconomy, Max-Eyth-Allee 100, 14469 Potsdam-Bornim, Germany, & 7. Adaptive AgroTech Consultancy International, CA 93955, USA. (2018). Advances in greenhouse automation and controlled environment agriculture: A transition to plant factories and urban agriculture. *International Journal of Agricultural and Biological Engineering*, *11*(1), 1–22. https://doi.org/10.25165/j.ijabe.20181101.3210

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