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Mathematical Optimization of Vertical Farm Locations Advancing Sustainable Agriculture in Saudi Arabia

Amjad Aljuhani [1]; Rahaf Baghdadi [2]; Wafaa Alzahrani [3]; Deemah Aljuhani [4]

[1,2,3,4]Department of Industrial Engineering, Faculty of Engineering, King Abdulaziz University, Jeddah 21589, Saudi Arabia

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Abstract: The increasing demand for food production in dry regions requires innovative agricultural practices. Vertical farming presents a sustainable solution by optimizing space and resource utilization while addressing food security challenges. This study examines the feasibility of vertical farming in Saudi Arabia, using mathematical optimization to determine the most suitable locations for vertical farms in the country. A mixed-integer linear programming model was developed using AIMMS software, incorporating key parameters such as infrastructure compatibility, water availability, and energy consumptions. Data from government records and geospatial analysis were integrated to enhance model accuracy. The results identify seven optimal locations in five cities—Riyadh, Jeddah, Dammam, Tabuk, and Khamis Mushait—ensuring efficient lettuce production at minimized costs. Findings highlight the potential of vertical farming in urban settings, reducing water consumption and enhancing food accessibility. However, challenges such as high energy requirements and initial investment costs persist. Future recommendations include decentralized container-based farming, renewable energy integration, and advanced automation. By implementing these solutions, vertical farming can transition from a niche agricultural practice to a mainstream, sustainable solution for food security in Saudi Arabia. This research provides a strategic framework for policymakers and investors to promote sustainable urban agriculture in the Kingdom.

Keywords: *Vertical Farming, Location Optimization, Saudi Arabia, Mixed-Integer Linear Programming, AIMMS Software.*

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I. INTRODUCTION

A. Project Background

Vertical farming (VF), as a concept, is not a modern invention as many think, where it roots back to ancient civilization. One of the earliest and most iconic examples known to man is the Hanging Gardens of Babylon, constructed during the ruling of King Nebuchadnezzar II around 600 BC [1]. The gardens were designed with several terraces that displayed different types of plants and used irrigation methods, such as chain pumps, to move water from the rivers to the higher levels.

In 200 BC, the Aztec civilization developed a system called the Chinampas, which is defined as an ancient Mesoamerican land and water management system [2]. The system was created due to the rapid growth that was happening in Mexico, where they faced limited land. Doing so, they developed knowledge and practice that slowly expanded to the near water surface, transforming the city into a so-called “floating city”. This innovative approach allowed them to maximize agricultural output in challenging environments and is considered another early example of VF techniques.

In 1915, Professor Gilbert Bailey of University of Southern California coined the term “vertical farming”. His book, Vertical Farming [3], mainly dealt with the topic of using particular types of soils to grow crops. The term “vertical farming” in G. Bailey’s book differs from the current meaning, which refers to growing plants in layers in a multistory building or warehouse. However, the idea of a vertical farm came from the different theories presented in his book.

During the late 1990s, more attention was given to the concept of VF because of Dr. Dickson Despommier, a professor in microbiology and public health in Columbia University. Dr. Despommier is one of the pioneers in the field of VF, having popularized it in his 2010 book entitled "The Vertical Farm: Feeding the World in the 21st Century" [4]. He introduces in the book a vision of new agriculture: crops grown in stacked layers, often in a controlled environment, such as a building or greenhouse, using hydroponics, aeroponics, or aquaponics for delivering nutrients to the plants. This technique has several advantages: the water usage is less, the yield of the crops can be obtained all over the year, and this type of farming can be done in urban areas where the space is limited. Vertical farming merely refers to growing food on vertical surfaces as

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compared to the traditional farming in which crops are grown on horizontal surfaces. Using vertically stacked layers, farmers can yield significantly more crops on the same piece of land [5].

People would wonder why VF? Our agricultural systems are receiving very extreme pressure with the increase in the world's population. According to an estimate, the United Nations estimates that by 2050, there will be 9.7 billion people on earth [6], which shall be requesting up to 70% increase in food production. Simultaneously contributing to this increase, urbanization and environmental pollution is bringing land shortage accessible. In view of such developments, new techniques in agriculture become necessary-such as VF-which must make maximum use of the available space and resources in order to feed the world's continuously growing population sustainably.

Once Dr. Despommier popularized the term "vertical farming", multiple establishments started to form and launch. The first successful farming was by Sky Greens Farm in Singapore in 2012. They are considered the world's first farm that uses the aeroponics system [7], which will be explained below. By 2015, The Association for Vertical Farming, which was founded in Germany, expanded with regional chapters globally, facilitating collaboration and knowledge sharing in the VF community [6].

Despite the numerous advantages of VF, several challenges persist that can impact operational efficiency and crop quality for VF farmers and companies. One significant issue is the occurrence of rotten crops, which can arise from various factors such as improper nutrient management, high humidity levels, and pathogen presence in the growing environment [8]. Developing effective strategies to prevent crop rot will be essential for ensuring consistent operations and maximizing the benefits of this innovative agricultural approach.

As a groundbreaking solution to the critical issues of food supply and environmental sustainability, VF has gained favor. It is clear from the review of history above that the idea is not only a trend but rather an essential development in agriculture, having roots in both ancient civilizations and modern innovations. The increasing global population, in addition to the limitations caused by urbanization and a lack of farmland, highlights the urgent need for effective agricultural methods. Vertical farming is a potential alternative to traditional farming since it maximizes crop yields in limited locations by utilizing modern technologies and innovative techniques. By addressing food security and promoting sustainable urban environments, VF has the potential to clear the way for a more adaptable and resource-effective agricultural landscape in the future.

II. LITERATURE REVIEW

This literature review focuses on key areas of VF. It begins by discussing controlled environment agriculture and its significance in optimizing growing conditions. Next, it highlights the importance of VF. After that, it compares VF to traditional farming. The review then examines various techniques used in VF, including hydroponics, aeroponics, and aquaponics. Additionally, the role of advanced monitoring systems, such as artificial intelligence, along with the use of linear programming for space optimization after that it covers renewable energy sources and location optimization. Finally, it explores the development of VF in Saudi Arabia and discusses the challenges it faces.

A. Controlled-Environment Agriculture

As far as 10,000 years ago, crops' cultivation for food production remained the same as today. Farmers used nutrient-rich soils to plant seeds and harvested them to deliver to the people. However, Given the drawbacks of traditional crop-growing techniques and the rising need for food, there is now a more pressing demand for the transition to controlled environment agriculture (CEA), which is a more advanced and precise method of food production [9]. The word CEA describes agricultural systems that protect crops from outside factors and have the capacity to oversee, track, and regulate the environmental conditions of the growing area to increase yields that are more consistent throughout the course of the year [9]. Advanced technical equipment and sensors are used in CEA systems to monitor the developing unit completely. Automations and actuators are used to ensure consistent, ideal environmental conditions while improving energy management. For critical and instant decision-making, the Internet of Things (IoT) and wireless communication technologies build a communication bridge between hardware and user [9]. Although high-tech VF systems have many advantages, mentioned in Figure [1], the huge amount of energy used to provide sufficient indoor conditions for larger yields and higher-quality crops raises questions about the sustainability of indoor VF. Additionally, the business mostly depends on fossil fuels to supply the energy needed for artificial lighting and HVAC (heating, ventilation, air conditioning, and dehumidification) systems [10].

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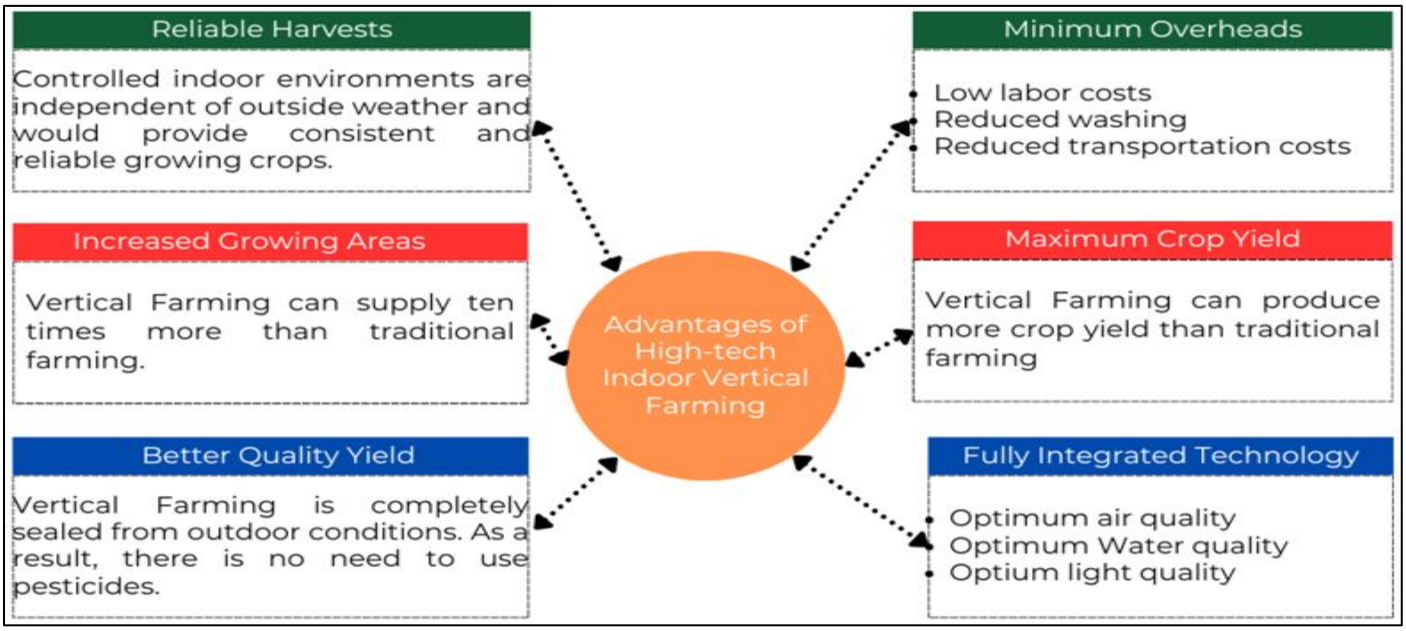

Fig 1 Advantages of High-Tech Indoor Vertical Farming [10]

B. Importance of Vertical Farming

Only 38% of global land is designated as agricultural, with only 11% suitable for cultivation. This presents significant land constraints, as projections indicate a mere 2% increase in agricultural land by 2040 [11]. The limited availability of land, combined with rising water scarcity, highlights the urgent need for sustainable farming practices to mitigate environmental impacts such as greenhouse gas emissions, soil depletion, and biodiversity loss. Vertical Farming provides a promising solution by allowing for efficient, resource-saving food production within urban environments, offering a year-round supply of crops, including fruits, vegetables, herbs, and medicinal plants. VF's strategic urban integration minimizes transportation logistics while enhancing food accessibility in densely populated and arid regions. For instance, in desert climates like Saudi Arabia, where average rainfall is limited to 70-100 millimeters per year and non-renewable water sources are projected to last only 14 more years at current extraction rates, VF's water-efficient approach offers a sustainable path to achieving food security [11]. By integrating VF into urban planning, cities in Saudi Arabia can enhance food resilience, reduce environmental impacts, and move towards a more sustainable and self-sufficient agricultural model.

C. Comparison Between Vertical Farming and Traditional Farming

Vertical farming and traditional farming diverge significantly in terms of crop variety, resource needs, and costs. Vertical farming is particularly effective for compact crops like small leafy vegetables and other salad leaves [12]. However, it has a limited capacity for a variety of crops. In contrast, traditional farming can support a wider range of plants, including larger staple crops of vegetables and fruits. VF conserves water significantly, using up to 90% less than traditional farming methods due to its vertical design, which requires much less land [13]. However, VF is energy-intensive, relying heavily on artificial lighting, climate control, and nutrient circulation, resulting in higher energy costs. In contrast, traditional farming benefits from natural sunlight and climate, leading to lower energy demands, but it requires more land and water [13]. From a cost perspective, VF has high startup costs and requires specialized labor [14]. As a result, it incurs higher operational expenses, even though it has the potential to produce up to ten times more crops per unit area compared to traditional farming methods [12]. In contrast, traditional farming generally has lower initial setup costs and takes advantage of a well-established and cost-effective labor model.

Overall, vertical farming presents certain challenges, such as limited crop variety, high energy consumption, and high startup costs. However, it provides a highly efficient and sustainable option for urban agriculture, particularly for growing high-yield, compact crops. As technology continues to advance, VF has the potential to become an increasingly valuable solution for addressing food demands in space-constrained and resource-limited environments.

D. Techniques Used in Vertical Farming

➢ *Hydroponics*

Hydroponics is the procedure of plant growth in the absence of dirt but using a nutrient-rich water solution. It obtains its name from the Greek words for water and labor. It was Robert Boyle who first successfully grew spearmint with water alone [15]. During the beginning of hydroponics, scientists such as Knop and Sachs investigated plant nutrition by determining necessary nutrients for development [15]. Even though the studies were mainly scientific, W.F. Gericke was instrumental in applying hydroponics for farming purposes. In 1930, Gericke patented the Nutrient Film Technique (NFT), a method in which plants are cultivated over a constant stream of nutrient solution [15]. NASA started to study hydroponics with the Biomass Production Chamber from 1988 to 2000. This study developed sustainable food production techniques appropriate for space missions. This method enabled the growth of plants without soil by providing a continuous flow of nutrient-rich solution directly to the roots [16].

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In 2011, Sky Greens was the first hydraulic-powered vertical farm with a low carbon footprint. It features over 1,000 vertical towers, each nine meters tall by using hydroponically cultivating vegetables. The farm employs A-Go-Gro technology, which incorporates rotating trays around aluminum towers within a compact 5.5 square meter footprint. Developed in collaboration with Singapore's Agri-Food and Veterinary Authority (AVA), this hydroponic system is highly energy efficient, consuming only 40 watts of electricity per tower. Sky Greens use natural sunlight and process all organic waste on-site. Its hydroponic method produces vegetable crops five to ten times greater than traditional agriculture. The company strives to expand in China, including Tianjin, Beijing, Fujian, and Xian, as well as in New York, Puerto Rico, and the Middle East [17].

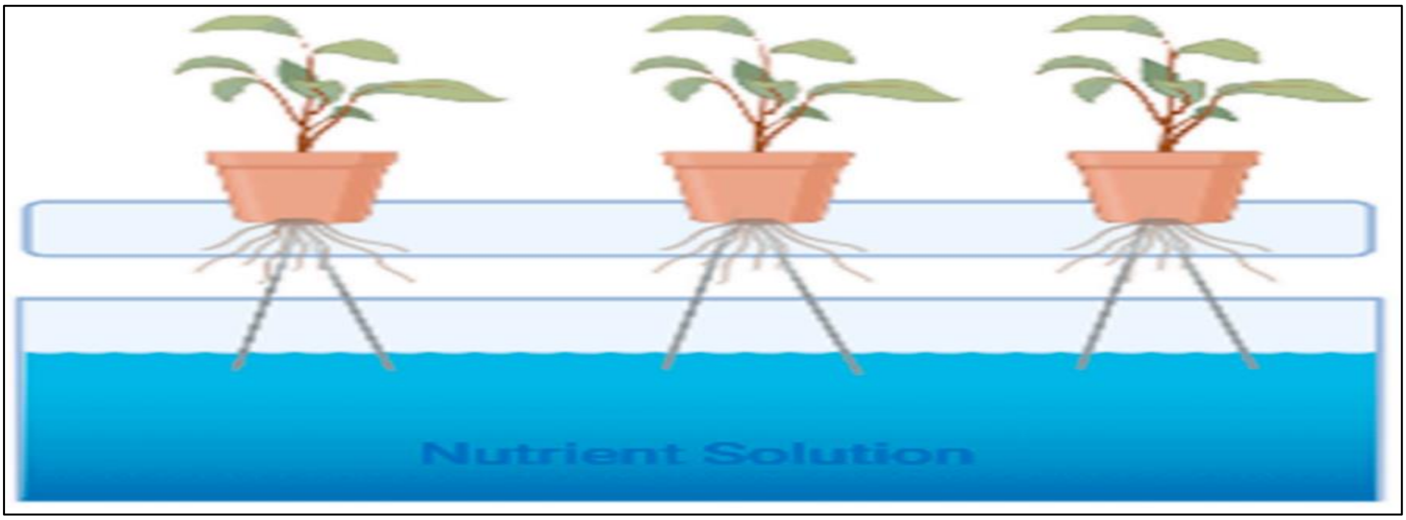

Fig 2 Hydroponics System [18]

➢ *Aeroponics*

Aeroponics is a technique for cultivating plants that utilize a mist of air and nutrients instead of soil. It consumes less water and space compared to traditional agriculture. The study of aeroponics started in the 1920s. In the early 1940s, aeroponics was for research rather than application. In 1983, Growth Technology International (GTi) launched the Genesis Rooting System, the first commercial aeroponics system. The device uses a microchip for control and is connected to an electrical outlet and a water faucet. Following that, National Advisory Committee for Aeronautics (NASA) conducted research in the 1990s to further explore the potential of aeroponics. Their studies showed the effectiveness of the process, wherein biomass was 80% greater than in hydroponics [19]. Based on such developments, AeroFarms was founded in New York in 2004 and has since moved to Newark, NJ in 2015. With proprietary technology in aeroponics, AeroFarms is a world leader within the VF industry and has risen through the ranks to date. AeroFarms claims that with the use of this technology, they are able to grow 75 times more plants than the average technologies of farming. The company is intending to move into markets [20].

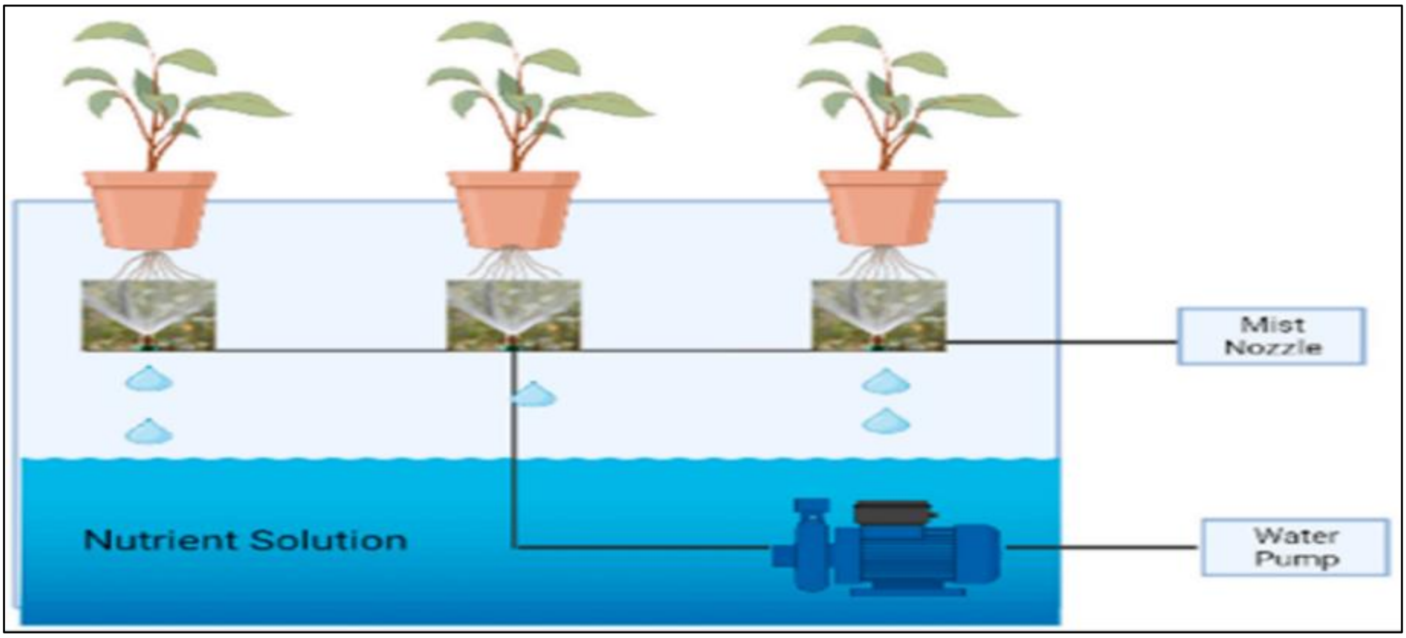

Fig 3 Aeroponics System [18]

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➢ *Aquaponics*

Aquaponics is a soil-free cultivation method that combines hydroponics and aquaculture, providing plants with nutrients derived from fish [15]. While recognized as a technique since the 1970s, its origins go back to about 5 CE in South China, where rice was combined with fish farming, an early form of aquaponics that later spread throughout Southeast Asia. Today, aquaponics stands out as an ecologically responsible way of producing food. Nevertheless, the industry is confronted with regulatory issues caused by the overlap of jurisdictions between different agencies, making it difficult for producers to obtain approval. This scenario highlights the immediate necessity for synchronized regulations and precise definitions. International organizations like Food and Agriculture Organization (FAO), World Health Organization (WHO), and European Union (EU) are engaged in the development of standards for food safety and animal welfare in aquaponics. Although aquaponics is a relatively new field with few peer-reviewed studies, there is a quickly increasing interest in it. The high "hype ratio" indicates a growing acknowledgment of its potential in sustainable agriculture, by comparing public interest to academic output. Aquaponics' future appears bright, thanks to experts' contributions and discussions on its technical, economic, and environmental impacts [21].

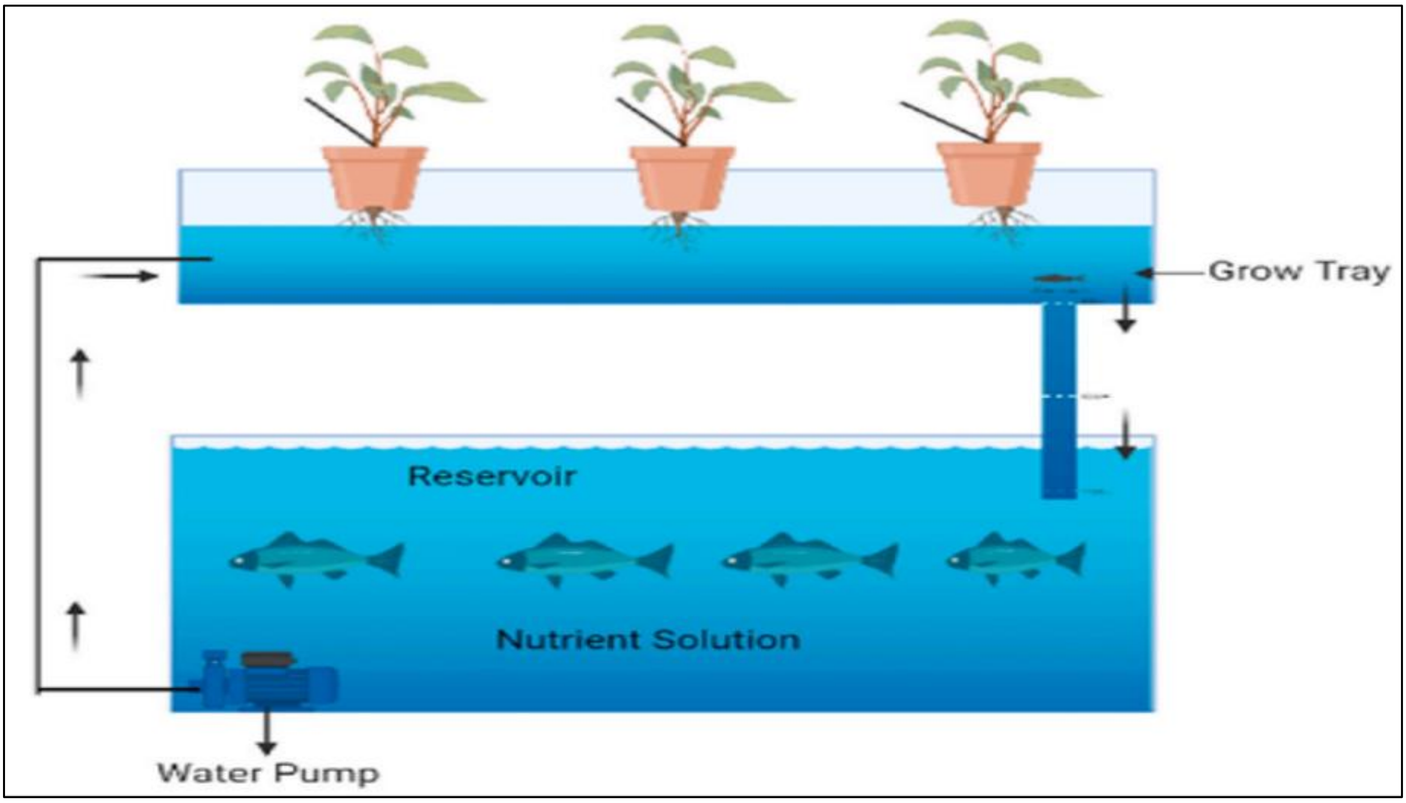

Fig 4 Aquaponics System [18]

Table 1 Farming Methods of Vertical Farming

Farming Method	**Characteristics**	**Benefits**	**Implementation Technologies**
Hydroponics	Soilless based, water is the growing medium	Fosters rapid plant growth, eliminates soil-related cultivation problems, reduce the use of fertilizers or pesticide	Computerized and monitoring systems; Cell phones, laptops, and tablets; Food growing apps; Remote control systems and software (farming-from-afar systems); Automated racking, stacking systems, moving belts, and tall towers; Programmable LED lighting systems; Renewable energy applications (solar panels, wind turbines, geothermal, etc.); Closed-loop systems, anaerobic digesters; Programmable nutrient systems; Climate control, HVAC systems; Water recirculating and recycling systems; Rainwater collectors; Insect-killing systems; Robots[22]
Aeroponics	A variant of Hydroponics, it involves spraying the roots of the plants with a mist or nutrient solutions	In addition of Hydroponics benefits, it requires less water	
Aquaponics	It integrates aquaculture (fish farming) with hydroponics	Creates symbiotic relationship between the plants and the fish, it uses the nutrient-rich waste from fish tanks to “fertigate” hydroponics production beds, and hydroponic bed cleans water for fish habitat	

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E. Advanced Monitoring Systems

Vertical Farming became a very strong area of growth in research and development of all sorts of modern technologies and methods, which have been striving to enhance the sustainability, efficiency, and productivity of urban agriculture. More emphasis is being given by the researchers to understanding market trends and the choice of consumers. This involves the identification of demand for different crops and addressing issues such as urban food deficiency using VF as a means of ensuring food security and a reduction in food miles. On the other hand, research is also targeted on system development and optimization, standards, and control concepts for VF operations. That would encompass crop cultivation techniques improvements and resource use efficiency as a factor in cost and environmental controls. More recently, there has been an emphasis on understanding the microclimate within vertical farms and how different environmental conditions affect plants to ensure high-quality and high-yielding productions and to successfully grow crops under controlled environments [21].

The evolution of Artificial Intelligence (AI) in sustainable VF represents a significant shift from initial spatial innovations to the integration of advanced technologies. Originally developed to address the limitations of traditional agriculture, VF aimed to optimize food production by maximizing yields, reducing water usage, and mitigating climate-related uncertainties. Early vertical farming relied on innovative designs and efficient cultivation methods, but the introduction of AI marked a transformative change, ushering in precision agriculture. Initial AI applications focused on automating environmental control systems to optimize conditions for plant growth [23]. AI and data analytics, which optimize crop growth by analyzing environmental factors such as temperature, humidity, and light intensity, allowing for real-time adjustments to ensure optimal growing conditions and minimize resource wastage [23,24]. In recent research [25], AI-powered systems are used to monitor and optimize environmental conditions in vertical farms, including temperature, humidity, illumination, and nutrient levels. It also serves to boost crop growth and resource efficiency.

The combination of AI and data analytics improves predictive skills, allowing vertical farms to foresee problems and take quick, educated action. Moreover, the study pointed out the important role of sustainable food production systems, especially during the COVID-19 pandemic which has sparked greater interest in urban smart vertical farming (USVF). Furthermore, AI has played a crucial role in automating operations that reduce human work and assure a steady food supply during lockdowns. AI has also played a crucial role in automating operations that reduce human work and assure a steady food supply during lockdowns. This study demonstrated AI's ability to improve food safety and biosecurity through increased monitoring systems. To further explore the role of AI in vertical farming, a study examined its impact on data-driven decision-making and operational efficiency. The study showed how AI improves farm management through predictive maintenance, optimizes crop yields by assessing environmental parameters, and allows for early detection of pests and illnesses. It also investigated the application of AI for automating tasks such as lighting adjustments and precision watering, as well as using robotics for planting and harvesting [24].

Vertical Farming techniques such as hydroponics and aeroponics have proven to be effective in growing a wide range of vegetables, fruits, and herbs. By using the Internet of Things (IoT), farmers were able to automate various operations, continuously monitoring and adjusting factors such as pH, water levels, temperature, and light intensity. For example, temperature sensors played a vital role in alerting farmers to prevent freezing during winter, while electrical conductivity (EC) and pH sensors ensured that nutrients were distributed properly. Furthermore, the application of machine learning (ML) further enhanced these processes, enabling systems to autonomously manage plant growth and nutrient levels. This powerful combination of IoT and ML led to significant improvements in both crop productivity and quality. A ML and IoT-based vertical farming system was structured around three main components: input, the ML system, and output. IoT sensors collected environmental data, which was analyzed to provide predictive insights that improved farming practices. While IoT and ML were utilized in both vertical and traditional farming for data collection and management, the key difference was in scale; traditional farming required a greater number of sensors and more complex models, whereas vertical farming operated on a smaller scale with fewer sensors and more straightforward, precise models [18]. Moreover, the IoT is an important tool by providing continuous monitoring of these factors, enabling accurate delivery of nutrients and irrigation management, which further enhances resource efficiency [21,24].

According to [25], it has been emphasized that incorporating IoT technology into USVF systems is important, demonstrating that this integration could lead to major enhancements in resource efficiency by real-time monitoring and control of critical environmental factors such as temperature, humidity, and nutrient levels. Furthermore, continuous advances in IoT technology are predicted to improve the efficiency, scalability, and economic viability of vertical farming, making it an essential tool for solving global food security challenges [26].

Automation and robotics have highlighted the potential for accelerating VF operations, reducing labor costs, and improving productivity. These technologies are used to automate processes like planting, harvesting, and crop health monitoring [22,24]. A study underlined the revolutionary potential of automation and robotics in VF, emphasizing how powerful they are to redefine agricultural processes. It focused on the advantages of robotic planting, harvesting, and maintenance, which resulted in higher precision, efficiency, and scalability, lower labor demands, and better resource usage, ultimately making vertical farming more sustainable and cost-effective [27].

Sustainable practices are also a key concern, with research highlighting the importance of sustainable practices in VF, such as the use of solar panels, LED lighting, and water-efficient irrigation systems, to reduce the carbon footprint of

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these operations [22,24]. As per [27], the researchers investigated the possibilities for vertical farming to improve urban food security and sustainability. Their findings pointed out the critical role of architectural design (green walls, modular systems, adaptive reuse of existing structures) in maximizing space and reducing environmental effect, as well as the significance of technology in enhancing resource efficiency and automating manufacturing processes.

Space should be utilized efficiently in VF to maximize crop production within limited spaces. VF involves growing crops in multiple layers, enabling optimal use of confined spaces. This system significantly increases plant production compared to traditional farming methods, but inadequate space utilization can lead to underutilized growing areas, reducing overall output potential. By using linear programming (LP), vertical farms maximize space utilization, ensuring every layer and shelf is fully optimized. This approach allows for precise placement of crops, maximizing yield within the available area [28]. In urban environments or regions with limited arable land, optimizing space utilization is critical for achieving sustainable, high-yield production in vertical farming systems.

Energy consumption plays a big role in VF, where it is known amongst farmers and companies that initial and operational costs are considered high. With the new focus on shifting industries to clean and sustainable aspects, VF companies are changing to renewable energy resources to reduce its carbon footprint. A promising technology is using wind turbines to generate heat and electricity, where Wind Harvest, a VF company in Wyoming, United States, has implemented vertical axis wind turbines (VAWTs) into their system [29]. Although VAWTs can capture wind from all directions, horizontal axis wind turbines (HAWTs) are better in terms of higher energy conservation, reliability, and adaptability [30]. A great tool to simulate for mechanical purposes is Computational Fluid Dynamics (CFD) Fluent, a simulation method to run mechanical analysis and element models [31]. In [31] used the simulation to compare different width and sizes of HAWTs to find the optimum result to generate the most energy.

Selecting suitable locations for VF in Saudi Arabia is crucial for enhancing food security through resource efficiency and sustainable practices. Covering approximately four-fifths of the Arabian Peninsula, with an area of about 2,000,000 square kilometers, Saudi Arabia experiences significant regional climatic variation [32]. These diverse conditions, combined with the specific requirements of each crop, make strategic location selection essential for successful VF implementation. Identifying optimal sites ensures that the environmental and logistical factors align to support sustainable and productive vertical farming systems.

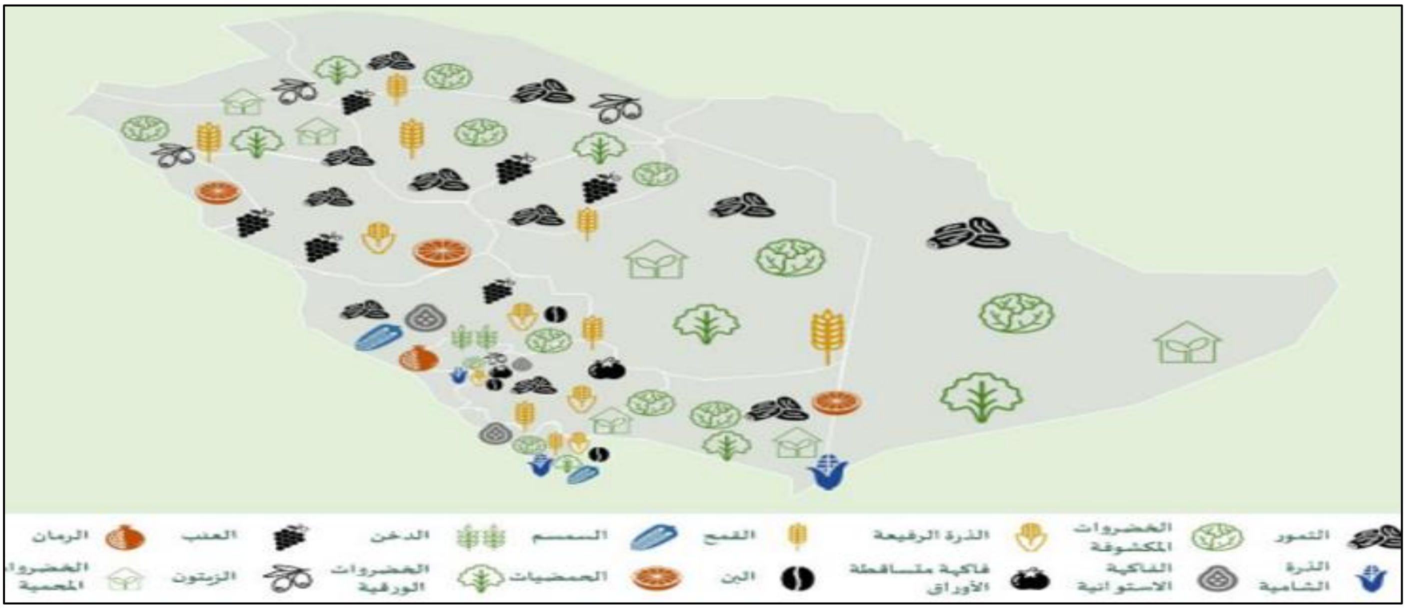

Fig 5 The Crops Production in The Regions [33]

The map above illustrates Saudi Arabia’s diverse agricultural zones for crops, showing dates, wheat, fruits, and vegetables cultivated in different regions. This variation underscores the need to carefully select VF sites that align with each region’s climate and resource availability. Similarly, implementing VF systems in regions like the Eastern Province, where industrial activities dominate and arable land is limited, can leverage available infrastructure to support local food production while addressing the scarcity of traditional farming areas. By situating VF systems in areas where traditional farming is limited by water scarcity or challenging climates, Saudi Arabia can maximize land productivity, support food security, and optimize resource use. This targeted approach allows VF to address regional needs effectively, helping bridge the gap in local food production and reducing import dependency.

F. Vertical Farming in Saudi Arabia

Vertical farming is a new agricultural technique that has been applied recently in Saudi Arabia due to the challenges of environmental conditions for traditional farming, there is a nature-triggered need for sustainable ways that meet food security [34]. Moraq is the first vertical farm in Saudi Arabia, and it produces more than 35 tons of organic leafy greens on

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just 700 sq. meters. Moraq highlights the significant water efficiency of hydroponic farming (more than 90% less water from conventional agriculture [35]. Moraq and Yas Health Group to develop a joint venture organization, the Regional Company, which will operate in Riyadh as it sets out to create a regional network of vertical farms. Initiative machines started operations in the fourth quarter of 2023 [36].

The Ministry of Environment Water and Agriculture has also launched the first commercial urban vertical farm in the local produce markets allowing the customers to purchase fresh organic food from the small farms that are located inside the supermarkets like the Danube in Riyadh. It is supervised by the Vice Minister of Agriculture Engineer Ahmed bin Saleh Al-Eyada, where it relies on modern technologies such as AI and the IoT to cultivate various vegetables such as lettuce, coriander, parsley, and broccoli that are mostly imported from other countries. In five years, the urban farming initiative expects to establish between 600 and 1,000 farms in Saudi Arabia's retail sector and satisfy at least 20-40% of all vegetable demand. It will protect resources, return balance to its natural state, and use more short-cycle material flows. Consumers enjoy improved produce quality that stays fresh for five times longer than usual, while urban farms bring jobs to local communities, promote cleaner surroundings, and reduce labor needs, leading to increased profits. In general, these initiatives mark a notable improvement in the ability to produce local food, supporting sustainability and tackling food security issues in Saudi Arabia [37].

G. Challenges in Vertical Farming

Even though vertical farming is a very promising direction in agriculture, it faces several challenges, particularly in areas with specific environmental limitations. First, crops require artificial light, which necessitates high energy consumption because one can hardly rely substantially on natural sunlight in a vertical farm. Another crucial challenge has to do with water management since the tall building might face some logistical difficulties trying to pump water upwards to a higher floor, which is vital in those places where water is already in short supply. Besides, the cost of establishment for such advanced technologies as hydroponic and aeroponic systems is very high. Also, the lack of soil and other conventional farming methods may raise concerns over the artificiality of vertical farming [38]. These challenges may face Saudi Arabia in vertical farming.

H. Alternative Analysis

VF is a relatively new concept in Saudi Arabia, and there are limited studies available on the topic. Four alternatives have been identified, representing key areas of exploration in VF that could contribute to overcoming challenges and improving the efficiency, sustainability, and adaptability of these systems. Each alternative brings unique solutions that address specific issues such as resource optimization, automation, and energy consumption. By putting these methods into consideration, VF may advance toward a more sustainable agricultural system. These alternatives are important for discussion and consideration when evaluating the future of VF in Saudi Arabia.

➢ *Alternative A: Artificial Intelligence*

The incorporation of AI technologies—such as machine learning, computer vision, the IoT, and robotics—is essential for unlocking the full potential of vertical farming. Machine learning algorithms improve accuracy in crop yield prediction, optimize resource usage, and drive data-informed decisions to respond effectively to environmental conditions. Computer vision could enable real-time non-destructive plant health analysis, automated harvesting, and quality control. IoT devices are vital in the field of environmental variables, nutrition, and irrigation control. It brings precision, with efficiency in resource use being multiplied. Robotics automates labor-intensive tasks such as planting and packaging, hence increasing the productivity of the crops and reducing labor costs. Those are the applications and benefits brought about by AI technologies that keep on impacting the future of sustainable vertical farming [23].

Automation in vertical farming effectively addresses main problems such as high labor costs, skill shortages, and the need for increased efficiency. It minimizes human interactions; therefore, it reduces disease risk, increases safety, and production inside these systems. Key automation applications include seeding, transferring seedlings, automated watering, lighting, fertilization, crop monitoring through visual systems, harvesting, and cleaning. These technologies contribute to cost savings, provide critical data for optimization, and enable IoT-connected farming-precise monitoring and feedback on growth conditions. The rise of mini vertical farm systems for home or small business use showcases the benefits of automation, as these systems autonomously manage climate, hydroponics, LED lighting, and growth through mobile apps. However, yielding optimization due to the need for manual harvesting and planting is preventing complete automation at present. On the other hand, fully automated vertical farming would involve all the processes, from sowing to planting, lighting control, fertilization, harvesting, and cleaning. Such smart, software-driven installations make it possible to monitor everything in real time and allow for precise planting and much faster sowing, with a speed higher by factors of 10 to 30 compared with manual methods in a 20-layer vertical farm [24].

➢ *Applications of AI in Vertical Farming*

The application of AI to detect early indicators of plant diseases, predict crop yields, and utilize automated systems in VF is an important advancement in agricultural technology. AI revolutionizing food safety and sustainability by enabling the detection of spoiled produce [18]. Advanced image recognition and ML enable AI systems to identify early signs of spoilage imperceptible to the human eye by examining minute visual details.

Rajesh Megalingam's group has come up with a unique technique for detecting food spoilage by combining image classification, machine learning, and artificial intelligence. The technique utilizes deep convolutional neural networks (CNNs) and computer vision with color classification using k-means clustering Megalingam used the HSV (Hue, Saturation, Value) values in images to detect spoilage in fruits and vegetables. Additionally, the research was conducted using the Anaconda prompt on the Jupyter Notebook platform, demonstrating a

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practical application of artificial intelligence for food quality management. The system achieved an excellent 95% accuracy rate, demonstrating its ability to detect rotten food and significantly reduce human error and labor costs associated with manual inspections. Additionally, it does not only detect spoilage but also monitors environmental factors, such as gas emissions, humidity, and temperature, to improve food preservation [39]. That would demonstrate AI is improving food safety and reducing waste, as well as its current benefits across many other different industries.

Combining AI technologies and vertical farming techniques provides a transformative approach to modern agriculture, addressing concerns of population growth and climate change. Furthermore, ML and deep learning (DL) models, often integrated into IoT systems with smartphone interfaces, offer autonomous disease detection. Several studies highlight the effectiveness of these approaches: random forests and Support Vector Machine (SVMs) achieved high accuracy (94.1%) in apple fruit disease classification, a low-power CNN model using knowledge distillation reached 99.4% accuracy in a smart hydroponics system, and other studies using CNNs and SVMs demonstrated high accuracy (98-99%) for disease detection in various hydroponic and aeroponic systems for lettuce, ripe plants, and tomatoes [40-42]. Moreover, Crop yield prediction in VF depends on the data of IoT sensors for light, temperature, humidity, and nutrients. The data is analyzed using machine learning models such as Support Vector Regression (SVR), Multiple Variable Regression (MVR), and Random Forest (RF), achieving 99.27% accuracy in hydroponics. The efficiency of these models depends on high-quality data and preprocessing techniques.

Nutrient and water management in VF can be optimized using IoT and machine learning. Algorithms in predictive analytics provide predictions for the optimal control action for pH and nutrient levels. One of the most accurate algorithms is XGBoost, yielding an accuracy of about 97.9% in aquaponics. Also, Real-time automation through IoT devices allows farmers to monitor conditions by mobile apps, requiring continuous internet connectivity, which can be enhanced by adjusting data collection intervals [18]. Table [2] highlight the Technological Approaches of AI and ML specifically in vertical farming [23,24]:

Table 2 AI Techniques in Vertical Farming

Machine Learning Model	**Description**	**Applications**
Support Vector Regression (SVR)	Effective for predicting continuous outcomes based on input featuresw like nutrient levels and environmental conditions.	Used in yield prediction and growth modeling for various crops.
Random Forest (RF)	Provides robust predictions by aggregating results from multiple decision trees, enhancing accuracy.	Applied in disease detection and crop yield estimation, offering high accuracy in predictions.
Extreme Gradient Boosting (XGBoost)	Known for its speed and performance in handling large datasets, making it suitable for real-time yield predictions.	Utilized in scenarios requiring quick decision-making, such as optimizing resource allocation.
Deep Neural Networks (DNNs)	Utilized for complex pattern recognition and predictions from large datasets, particularly in image analysis.	Employed in assessing plant traits and health through image data analysis.
Convolutional Neural Networks (CNNs)	Specialized in processing grid-like data, such as images, to detect features relevant to plant growth.	Used for image classification tasks to monitor plant health and growth stages.
YOLO (You Only Look Once)	An AI-driven computer vision technique effective in real-time object detection within crops.	Facilitates timely adjustments to growth conditions by monitoring plant health through images.
Fuzzy Logic (FL)	A form of many-valued logic that deals with reasoning that is approximate rather than fixed and exact.	Applied in decision-making processes where uncertainty exists, such as irrigation scheduling and nutrient management.
Artificial Neural Networks (ANNs)	Computational models inspired by the human brain that can learn patterns from data through interconnected nodes.	Used for predictive modeling of crop yields and disease detection based on historical data inputs.

- *Alternative B: Space Utilization*

Vertical farming is a modern farming technique that aims to increase crop output by growing plants in vertical layers, making efficient use of limited space. VF designs focus on maximizing space efficiency because space is usually the costliest element in agricultural facilities. This is important because maximization of space reduces cost, enables cities to grow their food, reduces transportation expenses, and, finally, carbon emissions.

Linear programming can be used to improve space utilization in vertical farming by optimizing the arrangement of plants on vertically stacked shelves. This method focuses on managing crops based on their specific environmental needs, such as temperature, humidity, and light, which vary at different growth stages. By doing so, the space in vertical farming systems can be used efficiently, accommodating each plant's requirements while maximizing the available growing area. The goal of the model is to make the most of limited space by minimizing the need to rearrange shelves and reducing the movement of crops between shelves. This minimization helps prevent crop damage and increases operational efficiency. The model considers daily environmental adjustments on a shelf-by-shelf basis, ensuring that crops are placed in optimal growing conditions, which helps avoid overcrowding and ensures that space is used to its full potential [28]. This LP-based optimization technique shows how thoughtful planning can enhance the efficiency of vertical farming systems, especially in areas with space limitations.

This LP-based optimization technique is unique, as it is the only research or model applying linear programming for space utilization in vertical farming. This technique would promote more space utilization, and less waste, hence contributing to sustainable farming, especially in urban areas or countries that have limited arable land, where maximum output from crops is key.

- *Alternative C: Renewable Energy Sources*

As mentioned in the literature review, VF can use an extensive number of resources, especially in terms of energy consumption. To solve the inefficiencies related to lighting, climate control, and other operational actions, energy optimization is crucial. Integration of renewable energy sources in vertical farming systems optimizes energy efficiency, enhances environmental sustainability, and maximizes agricultural yield [9]. There are many forms of renewable energy sources that target energy, water, and wind. Photovoltaic (PV) systems are considered a solar energy technology, that are essential for integrating renewable energy into vertical farming, as they improve operational efficiency and sustainability [43]. They are embedded onto rooftops of existing buildings without the need to create a specific area to place them in. These solar-powered systems power up vertical farms' many components, which are becoming more and more acknowledged for their potential to transform urban agriculture.

Another well-known technology is wind power, where two main turbines can be used: VAWTs and HAWTs. As mentioned in the literature review, HWATs are considered a better option for energy optimization and efficiency [30]. Due to the nature of this project, a way to implement renewable energy resources into a VF system is through a simulation model. Computational fluid dynamics simulation is an example of a method to implement and enhance the wind turbines in a VF building. This alternative would satisfy the first and second requirements of this project, however for the third one, there are not enough data and companies that currently are implementing renewable energy sources into their VF systems.

- *Alternative D: Location Optimization*

Saudi Arabia's agricultural strategy focuses on both water conservation and achieving self-sufficiency. The National Water Strategy in Saudi Arabia aims to reduce water usage from 19 billion cubic meters in 2017 to 6.2 billion cubic meters by 2030 [33]. This reduction is part of a broader plan to increase vegetable self-sufficiency from 70% to 100% by 2030 [33], ensuring a reliable supply of fresh produce for the population. However, the current number of vertical farms in Saudi Arabia is relatively low, highlighting the need for a strategic expansion of VF systems in suitable locations. Vertical farming provides an efficient method for utilizing land and water resources, making it a sustainable answer to Saudi Arabia's water scarcity issues. Unlike traditional agriculture, vertical farms consume significantly less water, which helps decrease reliance on non-renewable groundwater sources. By enhancing local vegetable production vertical farming can reduce the country's dependence on imports, resulting in a more stable and secure food supply. Saudi Arabia had a total of 410,986 agricultural holdings, with 349,323 of them actively used for agriculture.

This means that 69.4% of agricultural holdings are operational [32]. The distribution of these agricultural plots, shown on the below accompanying map, reveals higher concentrations of activity near major cities and farming hubs. Blue markers identify the locations of these holdings. This pattern suggests that many of these operational areas could also serve as potential sites for VF.

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Fig 6 Agricultural Holdings Across the Kingdom [44]

Effective VF site selection will not only help Saudi Arabia achieve its self-sufficiency goals but also promote sustainable resource use, making the country's agricultural sector more resilient and aligned with national water conservation targets. This process will involve using optimization programs like AIMMS to analyze and select locations that maximize resource efficiency, ensuring the best use of water, energy, and land while supporting sustainable vertical farming practices.

Table 3 Evaluating Alternatives

			Alternatives							
Criteria		**Weight (%)**	**Artificial Intelligence**		**Space Utilization**		**Renewable Energy Sources**		**Location Optimization**	
			Score	**Weighted Score**	**Score**	**Weighted Score**	**Score**	**Weighted Score**	**Score**	**Weighted Score**
1.	Ability to optimize resource utilization	40	9	3.6	7	2.8	8	3.2	9.	3.6
2.	Availability of references for Saudi Arabia	25	8	2	4	1	7	1.75	8	2
3.	Ease of applying in vertical farming in Saudi Arabia	20	7	1.4	6	1.2	6	1.2	9.5	1.9
4.	Potential for improvement in vertical farming	15	9	1.35	7	1.05	8	1.2	9	1.35
	Total	100		8.35		6.05		7.53		8.85

The table above shows four alternatives: Artificial Intelligence, Space Utilization, Renewable Energy Sources and Location Optimization. It examines the relative importance of each alternative concerning the four criteria. Percentage weight is assigned for each criterion, adding up to 100%; scores for alternatives range from 1-10 score, where 10 is highly effective and 1 represents low effectiveness. The team multiplied the weight by the scores for each criterion to evaluate the alternatives and choose the best alternative. Optimizing resource utilization has a weightage of 40% because of its significance, while the availability of references has a weightage of 25%, showing the significance of credible sources. The practicability of the application in Saudi Arabia in Vertical Farming was given an importance of 20% to gauge the applicability of the technology. The Potential for Improvement in Vertical Farming is 15%. The overall scores indicate that Location Optimization received the highest score of 8.85. Following that, Artificial Intelligence scored 8.35, and Renewable Energy Sources earned a score of 7.35. Lastly, Space Utilization by LP scored 6.05. Based on these weighted scores, optimization location was selected as the best alternative.

I. Project Requirements, Specifications, and Constraints

This section presents the requirements, specifications, and constraints essential for the research on optimizing vertical farm locations in Saudi Arabia.

➢ *Requirements*

- Gather information from the Ministry of Environment, Water, and Agriculture in Saudi Arabia on location suitability

- Collaborate with government agencies, agricultural experts, or private investors to gather insights and validate location suitability.
- Identifying the factors influencing the selection of locations for vertical farms

Table 4 Pairwise Comparison Chart

	A	B	C	SUM
A		1	0	1
B	0		0	0
C	1	1		2

The pairwise comparison method is used to provide a systematic and structured way to evaluate and prioritize requirements A, B and C by directly comparing them against each other. The values in each cell indicate the importance of the requirement relative to another based on the literature review. A value of one means a requirement is more important than another, while a value of zero means it is less important. The sum column shows the overall priority. Requirement C is the highest of priorities by 2, following Requirement A with a score of 1, being also important but not as critical as C, and then Requirement B which is the least important. The requirements are prioritized from highest to lowest as follows:

- Identifying the factors influencing the selection of locations for vertical farms
- Gather information from the Ministry of Environment, Water, and Agriculture in Saudi Arabia on location suitability
- Collaborate with government agencies, agricultural experts, and private investors to gather insights and validate location suitability

➢ *Specifications*

- Analyze case studies from diverse geographical locations to understand the applicability of vertical farming in various urban environments
- The final deliverable will be a comprehensive research report that includes an executive summary, methodology, findings, discussions, conclusions, and recommendations

➢ *Constraints*

- The timeframe of this research may constrain the extent of literature reviewed and the number of case studies analyzed.
- The resource information of vertical farming in Saudi Arabia is limited.
- Engaging stakeholders may be challenging due to their availability or willingness to share information related to their operations.

III. METHODOLOGY

A. Problem Statement

Saudi Arabia faces significant challenges in determining optimal locations and methods for implementing vertical farms due to its harsh climate, limited water resources, and diverse geographical conditions. Currently, there is no comprehensive system for identifying the most suitable locations for agriculture, which limits the potential for sustainable farming. This uncertainty hinders the country's ability to effectively adopt vertical farming as a solution to enhance food security and reduce reliance on imports. The country's vast desert landscapes and extreme temperatures make conventional agriculture difficult, leading to a high dependence on irrigation and non-renewable groundwater. With only a small percentage of land suitable for agriculture, the ability to produce enough food to meet domestic demand is limited.

B. Objectives

➢ Identify the optimal locations for a vertical lettuce farm in each of the five most populous cities across Saudi Arabia's main regions.

➢ Assess the potential economic impact of vertical farming in specific locations.

IV. MATHEMATICAL MODEL

A. Indices

i: Index for potential farm locations (17 farms)

j: Index for market locations (Jeddah, Riyadh, Dammam, Tabuk, Khamis Mushait)

B. Parameters

➢ *Cost Parameters*

1. $FixedCost_i$: Fixed cost per square meter for establishing a vertical farm at location i (SAR/ m²).
2. $LandCost_i$: Land cost per square meter at location i (SAR/ m²/year).
3. $WaterCost_i$: Water cost per kilogram at location i (SAR/kg).
4. $EnergyCost_i$: Annual energy cost per square meter at location i (SAR/ m²)

➢ *Land and Production Parameters*

1. $LandSize_i$: Available land size at location i (m²)
2. $Quantity_{i,j}$: Expected annual crop production per square meter (kg/ m²/year) delivered from farm i to market j

➢ *Demand and Logistics Parameters*

1. $Demand_j$: Lettuce demand in market j (5% of the population).
2. $Distance_{i,j}$: Distance between potential farm location i and market j (m).

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3. α_j: Weighting parameter for demand fulfillment (ensuring at least 5% of the urban demand is met).
4. $farmforeachcity_{i,j}$: Binary parameter to indicate the assignment of a farm to market j

C. Decision Variables

1. $y_i \in \{0,1\}$: A binary decision variable that equals 1 if a vertical farm is established at location i and 0 otherwise
2. $TotalQuantity_i$: The total quantity of lettuce produced by a specific farm in kilogram per year

D. Objective Function

The goal is to minimize the total setup and operational costs of a network of vertical farms across a number of locations while also meeting urban demand for lettuce in important cities. The function integrates fixed and variable costs related to infrastructure and operation, and production expenses.

The objective function is composition of two principal parts. Firstly, the fixed cost of establishment and operation per square meter is combined with land, energy, and area size costs, and then it is multiplied by the binary variable which connects all initial costs related to land purchase and construction and operation facility to annual scale with respect to the total area land used.

Secondly, water-related production costs relate to the cost of water and the volume in total. It treats variable costs for crops produced in volumes, with a focus on water usage. This is an important input to any vertical farming system. Each farm i's contribution to the overall cost is conditional on (y_i), ensuring that only selected locations are included in the final cost aggregation. Therefore, an objective function that results from all the above lays as the base for strategy that is cost-effective in deploying vertical farming systems.

The model enables a thoughtful evaluation of trade-offs between proximity to urban centers, land affordability, and operational utility costs. It also assists in pinpointing the most strategic farm locations to enhance food security and resilience. Furthermore, it provides a framework for measuring the cost-efficiency of sustainable urban agriculture practices. In addition, the formulation seamlessly integrates into a broader mixed-integer linear programming (MILP) model, allowing for the incorporation of demand fulfillment targets, supply chain logistics, and sustainability factors like water use efficiency making it both practical and adaptable for real-world planning and policy development.

$$\text{Min } Z = \sum_i \left((FixedCost_i + LandCost_i + EnergyCost_i) \cdot LandSize_i + WaterCost_i \cdot TotalQuantity_i \right) \cdot y_i$$

E. Constraints

➢ *Demand Fulfillment Constraint*

To ensure that the vertical farm network meets a specified fraction of the urban market demand, the aggregate production from all selected farms must satisfy:

$$\sum_i (Quantity_{i,j} \cdot LandSize_i) \cdot y_i \geq \alpha_j \cdot Demand_j \quad \forall j$$

➢ *Farm-to-Market Assignment Constraint*

Every market j must be served by at least one vertical farm, ensuring that production is locally accessible:

$$\sum_i farmforeachcity_{i,j} \geq 1, \quad \forall j$$

➢ *Distance Constraint*

To maintain logistical efficiency and reduce transportation costs, the distance between any selected farm and its corresponding market is restricted:

$$Distance_{i,j} \leq 200 \text{ km}, \quad \forall i,j$$

These constraints ensure that the selected sites are not only cost-effective but also practically viable from a distribution standpoint.

V. DATA ANALYSIS

A. Adopted Method

This project focuses on location optimization as the primary analytical method to achieve the objective. This approach systematically evaluates multiple potential locations for a vertical farm based on key indicators such as cost and demand. The goal is to determine the most efficient and cost-effective location by applying mathematical modeling and optimization.

➢ *The Adopted Method Considers the Following:*

- *Criteria Identification:*

Key factors influencing the location selection are identified, including the land cost and distance to market.

- *Data Collection:*

Relevant data are collected from various resources, including academic journals, research papers, case studies, and government records.

- *Mathematical Modeling:*

An optimization model is created and developed to quantify the objective, parameters, constraints, and variables.

- *Optimization Execution:*

AIMMS software, explained in section 4.5, is used to run the optimization scenarios and identify the best location using the predetermined objective.

- *Data Validation:*

The result of the model is visualized to ensure that the output is reliable, as well as using sensitivity analysis and cost analysis.

B. Data Collection

Collecting the data for this project was the most consuming part due to the extensive research needed and the lack of data for VF in Saudi Arabia to obtain accurate and

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relevant information. The data was gathered from various credible resources to reflect accuracy and reliability.

The most valuable sources were governmental records where data was obtained from resources such as the General Authority for Statistics, Saudi Ministry of Justice, and Ministry of Environment, Water, and Agriculture to ensure official demographic and economic data. Other resources include various the research papers referenced throughout the paper that provides in-depth analyses and theoretical foundations relevant to location optimization and/or VF information. Additionally, case studies brought the practical real-world aspect to the project.

The land prices and sizes were obtained from the Saudi Ministry of Justice [45]. This data provides official records on land value, allowing for a more realistic input into the model. Due to the limited vertical farming data specific to Saudi Arabia, the fixed cost was assumed to be 1,000 SAR per m². Since the chosen vertical farming (VF) technique for this project is hydroponics, the average energy consumption is estimated at 15.5 kWh/m² based on a typical range of 14–17 kWh/m² and, using an electricity price of 0.04 SAR per kWh, the energy cost was calculated accordingly [46]. A hydroponic system requires only 2.83 m³ of water to produce 1 ton of fresh lettuce [47]. Using this consumption rate and the prices of water from [48], the price for each m³ of water was found.

Table 5 Water Tariff [48]

Water Tariff After the Increase and Adding Consumption to Drainage	
Water Tariff	Total Consumption Tariff (SAR/m^3/month)
Less than 15	0.15
From 16 to 30	1.5
From 31 to 45	4.5
From 46 to 60	6
More than 60	9

To find the demand, each of five cities' population were found, then multiplied by the annual consumption of lettuce for each city. The current self-sufficiency demand rate for lettuce production using VF is 4.5% [49], and one of the purposes of this research paper is to increase the rate to 9.5%. The table below shows the population, average per capita lettuce consumption (kg), demand, and the demand after multiplying it by the self- sufficiency rate of each city.

Table 6 Demand per City

Lettuce Demand of the Five Cities				
City	Population	Average Consumption per kg	Demand	Modified Demand
Riyadh	7,820,000	4	31,280,000	1,564,000
Jeddah	4,940,000	4	19,760,000	988,000
Dammam	1,350,000	4	5,400,000	270,000
Tabuk	707,148	4	2,828,592	141,429.6
Khamis Mushait	588,000	4	2,352,000	117,600

To estimate the production capacity for lettuce, the research referenced a vertical farm currently under development in Saudi Arabia, designed with a 20,000m² growing area spread across 19 layers [50]. This facility is expected to yield up to 2,200 kg of leafy greens daily. Using this benchmark, the annual production per square meter was calculated, allowing for a more precise assessment of potential farm outputs at various scales.

By analyzing the examples of how vertical farms have been set up in different conditions and regions, insight has been gained regarding common challenges, best practices, and the decision-making processes involved in choosing an ideal location.

C. Software Used

Two software tools have been used to facilitate the data analysis and decision-making. **Microsoft Excel** was used for the collection of the data organization and preprocessing. **AIMMS** was a critical tool in developing and solving the optimization model, allowing for scenario analysis and strategic decision-making. It enabled the implementation of mathematical formulations that helped assess multiple location options based on various constraints and objectives. The third software used was **Power BI** that was used to display key information regarding the data as a dashboard.

AIMMS software played a crucial role in the validation process by enabling scenario testing and sensitivity analysis. The software is built as a fully integrated model development and solution environment to support complex mathematical problems [51]. It combines mathematical optimization, data analysis, and user-friendly interfaces to help businesses and individuals obtain better data-driven decisions. For this research paper, AIMMS was able to help in clearly listing the parameters, variables, constraints, and objective in a structured way. The software also was able to provide interactive maps and charts to present the data in a compelling way, however it was challenging to be able to display the interactive map of the farm locations clearly using the existing option in AIMMS. Therefore, Power BI was used as an alternative. Through these techniques, the model was tested under various conditions by adjusting key parameters, allowing for an assessment of its robustness and adaptability. Identifying potential weaknesses in different scenarios helped refine the model, ensuring it could produce reliable and stable results.

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Microsoft Excel supported the initial stages of data processing, facilitating tasks such as data cleaning, organization, and preliminary statistical analysis. By addressing inconsistencies and missing values, the dataset was prepared for optimization modeling.

Power BI was used to show data based on each city to display it in an interactive way for the viewer. The dashboard includes displaying the total demand of the selected city, the total cost of the farms, and a map of the farms locations which offers a visual representation of their locations and the distance from the center of the city. By using Power BI, the research paper ensures that the complex results from AIMMS are presented in a clear, visual, and engaging manner.

D. Data Analysis

This analysis examines farm site costs and production across five cities: Riyadh, Jeddah, Dammam, Tabuk, and Khamis Mushait. It utilizes Power BI for its powerful data visualization and interactive features. Each city has a dedicated Power BI dashboard that presents key metrics, including costs, production levels, demand, average cost, total cost, variance, and the geographical location of farms on an interactive map.

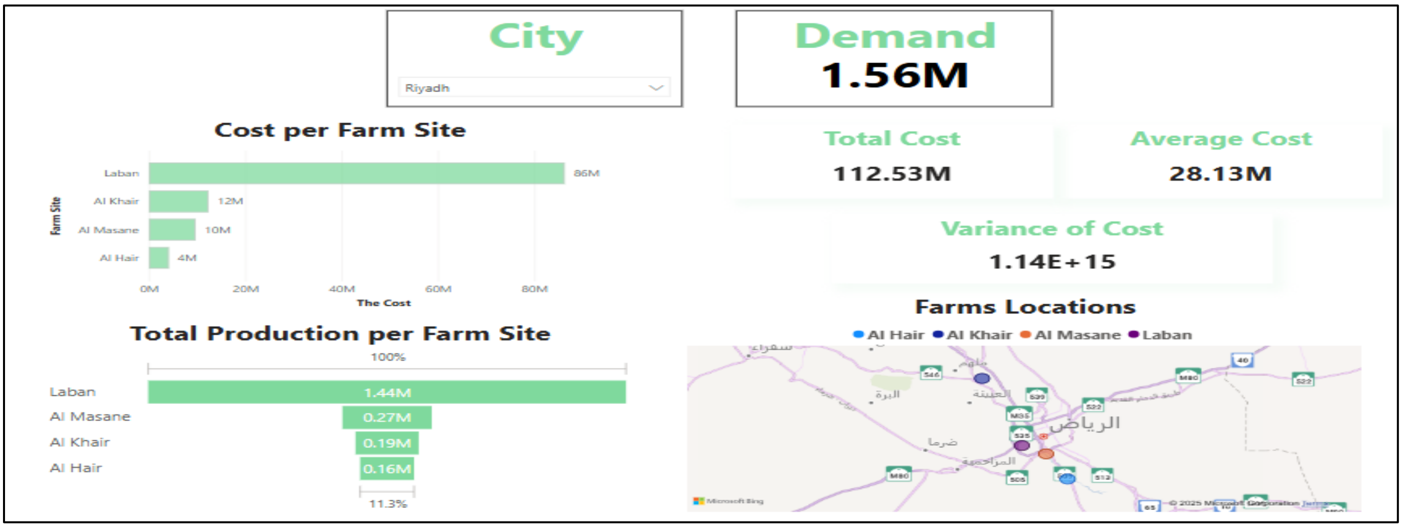

Fig 7 Riyadh Farm Sites Analysis Dashboard

This dashboard assesses the costs and production levels of farms in Riyadh, specifically determining whether each farm can meet the total demand of 1.56 million kilograms of lettuce. The costs of the farms show significant variation. Laban is the most expensive farm, with a cost of 86 million, which is well above the average cost of 28.13 million. Following Laban is Al Khair, priced at 12 million, which is below the average. Al Masane and Al Hair are more budget-friendly options, with costs of 10 million and 4 million, respectively. The total cost across all farms amounts to 112.53 million, and a cost variance of 1.14×10^{15} indicates a substantial disparity in costs among them.

In terms of production, Laban has the highest yield at 1.44 million, which is nearly enough to cover the total demand but still falls slightly short. Al Masane contributes 0.27 million, Al Khair yields 0.19 million, and Al Hair, the lowest producer, adds 0.16 million. Despite these contributions, no single farm can fully meet the required demand on its own.

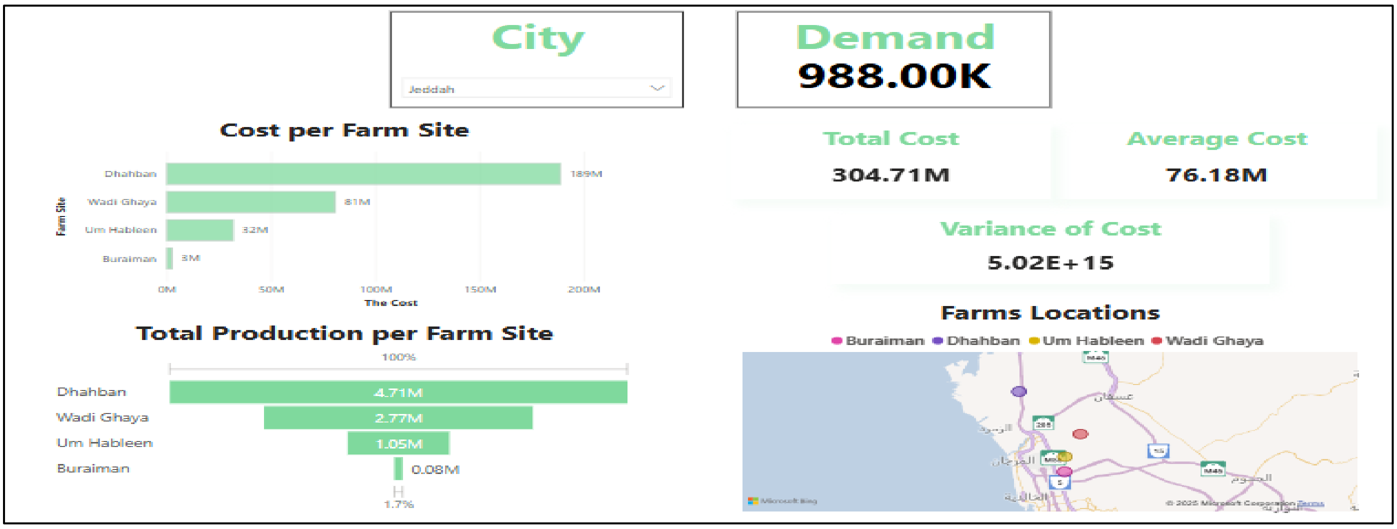

Fig 8 Jeddah Farm Sites Analysis Dashboard

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This dashboard analyzes the costs and production of farms in Jeddah, evaluating whether each farm meets the total demand of 988,000 kg of lettuce. Each farm has varying costs; some exceed, and others fall below the average cost of 76.18 million. Dhahban has the highest cost at 189 million, more than double the average, making it the most expensive farm. Wadi Ghaya follows with a cost of 81 million, which is slightly above the average but significantly lower than Dhahban. Um Hableen incurs a cost of 32 million, well below the average, making it more cost-efficient. Buraiman has the lowest cost at 3 million, making it the most budget-friendly option. The total cost across all farms is 304.71 million, with a variance of 5.02×10^{15}, highlighting a significant discrepancy in spending.

In terms of production, Dhahban produces 4.71 million, nearly 4.8 times the demand, making it the highest producer. Wadi Ghaya follows with a production of 2.77 million, almost 2.8 times the demand. Um Hableen produces 1.05 million, slightly exceeding the demand, while Buraiman produces only 0.08 million, which is insufficient to meet the demand.

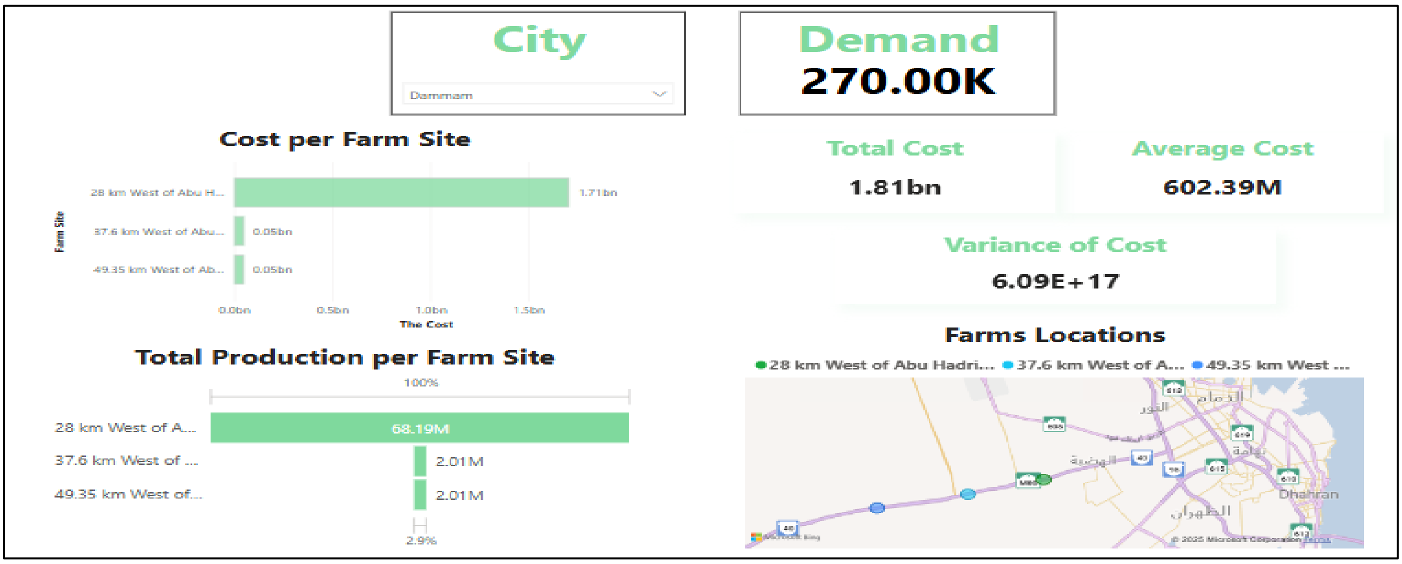

Fig 9 Dammam Farm Sites Analysis Dashboard

This dashboard evaluates the costs and production of farms located in Dammam, assessing whether each farm can meet the total demand of 270,000 kg of lettuce. The costs vary significantly; some farms exceed the average cost of 602.39 million, while others fall below this figure. The most expensive farm, which is situated 28 km west of Abu Hadriah, has a cost of 1.71 billion, far above the average. Conversely, more cost-effective options include farms located 37.6 km west of Abu Hadriyah Highway and 49.35 km west of Abu Hadriyah Highway, each with an approximate cost of 50 million, highlighting lower-cost alternatives. The total cost across all farms amounts to 1.81 billion, with a cost variance of 6.09×10^{17}, indicating significant disparities in spending.

In terms of production, the farm located 28 km west of Abu Hadriah yields 68.19 million, which significantly exceeds the demand. The farms 37.6 km west of Abu Hadriyah Highway and 49.35 km west of Abu Hadriyah Highway each produce 2 million, also surpassing the required demand.

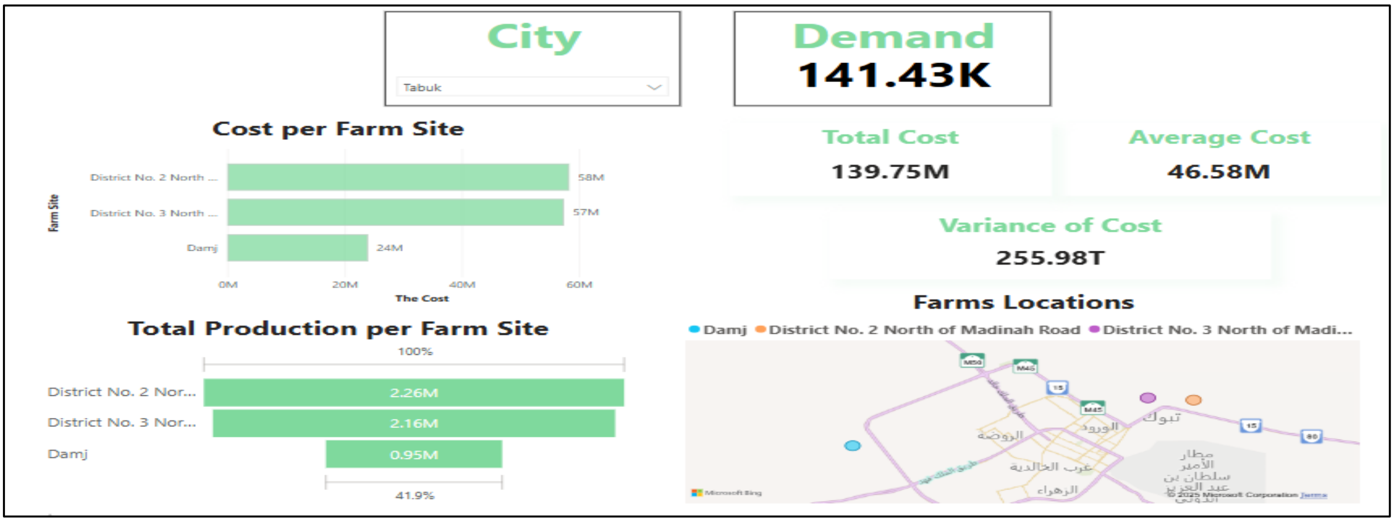

Fig 10 Tabuk Farm Sites Analysis Dashboard

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This dashboard evaluates the costs and production of farms in Tabuk to determine whether each farm meets the total demand of 141.43 thousand kilograms of lettuce. The cost per farm site shows noticeable variation. District No. 2 North of Madinah Road is the most expensive, costing 58 million, while District No. 3 North of Madinah Road follows closely at 57 million, both falling slightly above the average cost of 46.58 million. Damj, on the other hand, is the most cost-effective option, with a cost of 24 million. The total cost across all farms adds up to 139.75 million, and the variance of cost is 255.98 trillion, indicating a high degree of discrepancy in farm expenditures.

From a production standpoint, all farms produce well beyond the required demand. District No. 2 North of Madinah Road yields 2.26 million, District No. 3 North of Madinah Road generates 2.16 million, and Damj contributes 0.95 million kilograms. Each farm, individually, is more than capable of satisfying the demand, indicating a strong surplus.

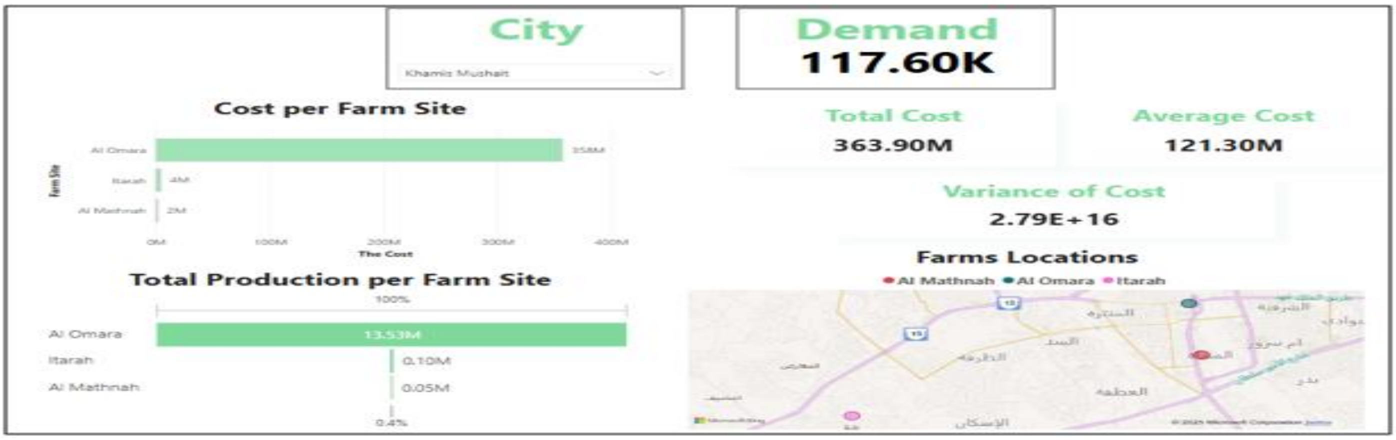

Fig 11 Khamis Mushait Farm Sites Analysis Dashboard

This dashboard analyzes the costs and production of farms in Khamis Mushait, evaluating whether each farm meets the total demand of 117.60 thousand kilograms of lettuce. The farm costs vary significantly. Al Omara is the most expensive, with a cost of 358 million, far above the average cost of 121.30 million. In comparison, Itarah is a more economical option at 4 million, and Al Mathnah is the most budget-friendly at just 2 million. The total cost across all farms is 363.90 million, and the variance of cost is 2.79×10^{16}, reflecting a substantial disparity in expenditures.

In terms of production, Al Omara has the highest yield at 13.53 million kilograms, massively exceeding the demand. However, Itarah produces only 0.10 million, and Al Mathnah produces 0.05 million both falling short of the 117.60K demand when considered individually. While these two farms cannot meet the demand alone, the combined production across all sites comfortably exceeds the required amount.

VI. RESULTS AND DISCUSSION

The AIMMS optimization model evaluated 17 potential farm locations across the five most populous cities in Saudi Arabia: Riyadh, Jeddah, Dammam, Tabuk, and Khamis Mushait, with the objective of minimizing total costs while ensuring local lettuce demand is met. The model incorporated key constraints such as demand fulfillment, farm to market assignment, and a maximum distance of 200 km between each farm and its respective market.

The AIMMS optimization model evaluated 17 potential farm locations across the five most populous cities in Saudi Arabia: Riyadh, Jeddah, Dammam, Tabuk, and Khamis Mushait, with the objective of minimizing total costs while ensuring local lettuce demand is met. The model incorporated key constraints such as demand fulfillment, farm to market assignment, and a maximum distance of 200 km between each farm and its respective market.

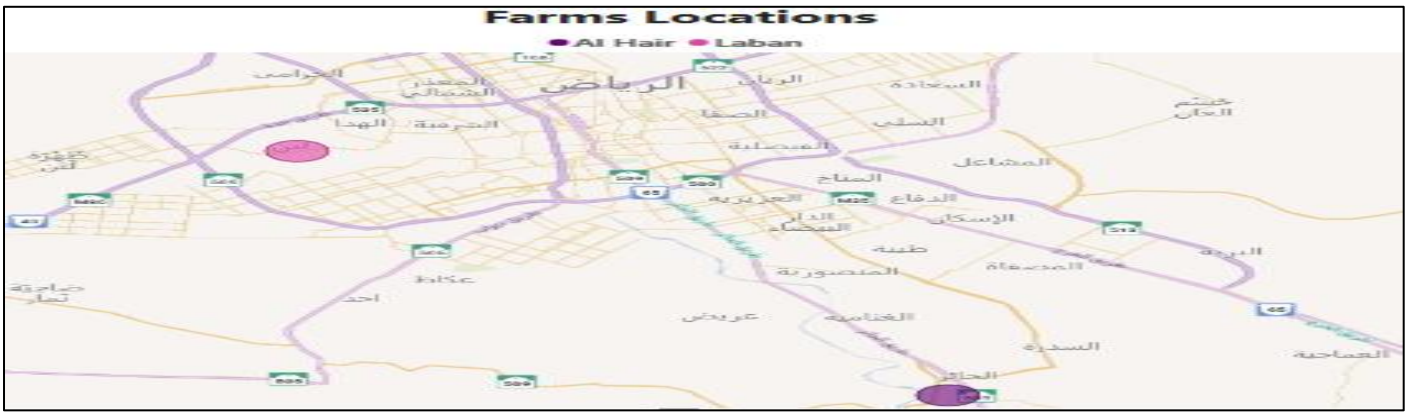

Fig 12 Optimal Farm Locations in Riyadh

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According to the map, two farm locations in the Riyadh neighborhoods of Laban and Al Hair have been strategically selected to meet the city's high demand for lettuce. The total cost for these farms is approximately 90,468,853.45 SAR, with 86,314,204.12 SAR allocated to Laban and 4,154,649.328 SAR to Al Hair.

In terms of production capacity, the farm in Laban is expected to produce 1,438,795.325 kg of lettuce, while the farm in Al Hair will contribute 162,527.2 kg, bringing the combined total production to 1,601,322.525 kg. This substantial volume will help satisfy the city's demand, ensuring a steady and sufficient supply of fresh lettuce for consumers.

Fig 13 Optimal Farm Locations in Jeddah

As shown in the map above, Umm Hablein has been identified as the optimal farm location in Jeddah to meet the city's high demand for lettuce. The total cost required for this farm is approximately 32,090,786.98 SAR.

Regarding production capacity, the farm in Umm Hablein is projected to yield 1,045,827.2 kg of lettuce. This considerable output will play a vital role in fulfilling the city's demand, ensuring a reliable and adequate supply of fresh lettuce for consumers.

Fig 14 Optimal Farm Locations in Dammam

The selected location for the farm is 49.35 km west of Abu Hadriyah Highway (120m) in Dammam, as indicated on the map above. The estimated total cost for this project is 50,232,131.03 SAR.

In terms of production capacity, the farm is projected to yield 2,007,500 kg of lettuce. This significant production will play a crucial role in providing a consistent and ample supply of fresh lettuce to consumers in the area.

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Fig 15 Optimal Farm Locations in Tabuk

As illustrated on the map, Damj has been chosen as the most suitable site for the farm in Tabuk. The estimated total investment for this project is 23,961,365.66 SAR.

Concerning production capacity, the farm Damj in Tabuk is expected to generate 947,111.73 kg of lettuce. This significant yield will help maintain a steady and sufficient supply of fresh lettuce for consumers in the area.

Fig 16 Optimal Farm Locations in Khamis Mushait

According to the map, two farm locations in Khamis Mushait Al Mathnah and Itarah have been strategically selected to meet the city's lettuce demand. The total cost for these farms is approximately 6,394,018.56 SAR, with 1,991,076.27 SAR allocated to Al Mathnah and 4,403,942.29 SAR to Itarah.

In terms of production capacity, the Al Mathnah farm is expected to yield 50,749.6 kg of lettuce, while Itarah will contribute 96,360 kg, resulting in a combined total production of 147,109.6 kg. This output exceeds the city’s demand of 117,600 kg, ensuring a stable and sufficient supply of fresh lettuce for consumers in Khamis Mushait.

Identifier	Production	FarmCost	Totalcost
Locations			
Laban	1,438,795.33	86,314,204.12	
Um Hableen	1,045,827.20	32,090,786.98	
49.35 km West of Abu Hadriyah Highway	2,007,500.00	50,232,131.03	
Al Mathnah	50,749.60	1,991,076.27	
Damj	947,111.73	23,961,365.65	
AlHair	162,527.20	4,154,649.33	
Itarah	96,360.00	4,403,942.29	
			203,148,155.67

Table 7 Optimal Farm Selection by AIMMS

To summarize the findings, Table above presents key information regarding the selected farms, including their respective production volumes and associated costs, as determined by the AIMMS optimization software. These farms

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are Laban, Um Hableen, 49.35 km west of Abu Hadriyah Highway, Al Mathnah, Damj, AlHair, and Itarah—were identified as the optimal combination to meet the projected lettuce demand. They were selected based on their ability to collectively fulfill production requirements at the lowest possible total cost. The total combined cost for this configuration amounts to 203,148,155.67 SAR.

A. Sensitivity Analysis

Sensitivity Analysis (SA), in the most general sense, is the study of how the outputs of a system are influenced by its inputs [52]. Based on that the inputs include key parameters such as land cost, water cost, energy cost, and production yield. The outputs of interest are the total cost and total production of vertical farming operations across the selected locations. Conducting sensitivity analysis allows for a deeper understanding of how variations in these inputs affect the model's outcomes and supports informed decision-making by identifying which factors have the greatest impact.

➤ *To Conduct this Analysis, AIMMS was used to Evaluate the model under two Adjusted Scenarios:*

- **+10% Scenario** (10% increase in cost and production inputs)
- **–10% Scenario** (10% decrease in cost and production inputs)

This approach allows for a clear comparison of how input variations impact the system, using AIMMS-generated tables to represent the changes in farm selection, total cost, and production across scenarios.

Table 8 AIMMS +10% Input Scenario Farm Selection

Identifier	Production	FarmCost	Totalcost
Locations			
Laban	1,582,674.86	94,949,655.61	
Um Hableen	1,150,409.92	35,302,795.77	
49.35 km West of Abu Hadriyah Highway	2,208,250.00	55,260,968.54	
Al Mathnah	55,824.56	2,190,326.08	
Damj	1,041,822.91	26,360,155.74	
Itarah	105,996.00	4,844,606.49	
			218,908,508.24

The table above presents the results of the scenario involving a 10% increase in key input parameters as generated by AIMMS. In this scenario, we have increased the costs of land, water, and energy, as well as production yield, by 10% across all vertical farming locations. This adjustment enables us to assess the impact of higher input costs on operational outcomes.

The total cost under this scenario increases to 218.89 million SAR, reflecting the higher expenses across farm operations. At the same time, total production rises to 6.14 million kg, due to the improved yield per site.

While the selected farm locations remain mostly the same as in the base scenario, Al Hair farm in Riyadh is excluded. This change is driven by the fact that, with the increased production capacity, Laban farm alone is now sufficient to meet the demand for Riyadh, eliminating the need for additional supply from Al Hair.

Table 9 10% decrease Scenario Dashboard

Identifier	Production	FarmCost	Totalcost
Locations			
Laban	1,294,915.79	77,679,485.56	
Al Masane	242,032.23	8,737,485.59	
Um Hableen	941,244.48	28,879,310.93	
Buraiman	73,354.05	2,459,814.23	
49.35 km West of Abu Hadriyah Highway	1,806,750.00	45,204,316.13	
Al Mathnah	45,674.64	1,791,852.31	
Al Hair	146,274.48	3,738,811.83	
Damj	852,400.56	21,563,058.02	
Itarah	86,724.00	3,963,327.17	
			194,017,461.78

The table summarizes the AIMMS results for a 10% reduction in key input parameters, following the same procedure applied in the +10% increase scenario. Land, water, and energy costs, as well as production yield, were each decreased by 10% across all vertical farming locations to evaluate the effects of diminished inputs. Under these

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conditions, total cost falls to 194.02 million SAR, while total production declines to 5.49 million kg. To offset the reduced output, two additional farms Al Masane and Buraimanare incorporated alongside the original sites (Laban, Um Hableen, 49.35 km West of Abu Hadriyah Highway, Al Mathnah, Al Hair, Damj, and Itarah). These results demonstrate that lower yields require a broader network of farms to meet lettuce demand.

Table 7 Key Results of sensitivity analysis

Scenario	Total Cost (SAR)	Total Production (kg)	Selected Farms
Base	203.15 million	5.75 million	Laban, Al Hair, Umm Hablein, Abu Hadriyah Hwy (Dammam), Damj, Al Mathnah, Itarah
+10%	218.89 million	6.14 million	Laban, Umm Hablein, Abu Hadriyah Hwy (Dammam), Damj, Al Mathnah, Itarah
–10%	194.03 million	5.49 million	Laban, Al Hair, Al Masane, Umm Hablein, Buraiman, Abu Hadriyah Hwy (Dammam), Damj, Al Mathnah, Itarah

The sensitivity analysis illustrates how variations in input can affect vertical farming operations. A 10% increase in both input costs and yields leads to the highest expenses (218.89 million SAR) and production levels (6.14 million kg). This scenario allows demand to be met with fewer farm locations; specifically, Al Hair can be eliminated, as Laban alone is sufficient to satisfy Riyadh's demand.

Conversely, a 10% decrease in input costs and yields lowers expenses to 194.03 million SAR and reduces production to 5.49 million kg. In this case, the addition of Al Masane and Buraiman is necessary to offset the shortfall.

The base scenario serves as a balanced benchmark, showing costs of 203.15 million SAR and production of 5.75 million kg across seven key farm locations. This comparison highlights the trade-offs between cost efficiency and production capacity under different input conditions.

B. Cost Analysis

Cost analysis is an important financial evaluation method used to systematically gather, categorize, and assess all costs associated with a project [53]. In this research, we apply it to vertical farming to examine how expenses are allocated, with a particular focus on distinguishing between one-time capital investments and recurring costs. Land cost is considered a one-time capital investment calculated once and assumed to apply indefinitely. In contrast, operational costs, such as energy, water, and production inputs, are treated as recurring expenses. Complementing this, break-even analysis is used to identify the point at which total revenue equals total cost, known as the Break-Even Point (BEP) the stage where the project neither generates profit nor incurs a loss [54]. Together, these tools provide a comprehensive understanding of the project’s financial structure and are essential for assessing long-term sustainability, identifying cost inefficiencies, and supporting informed decision-making in future planning.

Table 8 Annual Total Cost and Revenue

Year	1	2	3	4	5
Total Cost (SAR)	203,148,155.7	203,676,201.5	204,497,094.8	205,610,835.7	207,017,424
Revenue (SAR)	55,534,094.42	111,068,188.8	166,602,283.3	222,136,377.7	277,670,472.1

In this research, revenue is calculated by multiplying the total lettuce production by the market selling price of 9.66 SAR per kg [55]. The table above shows that production increases over time, total revenue experiences significant growth, rising from 55.53 million SAR in Year 1 to 277.67 million SAR in Year 5. Meanwhile, total costs have remained relatively stable, increasing only slightly from 203.15 SAR million in Year 1 to 207.02 million SAR in Year 5, reflecting limited operational cost increases.

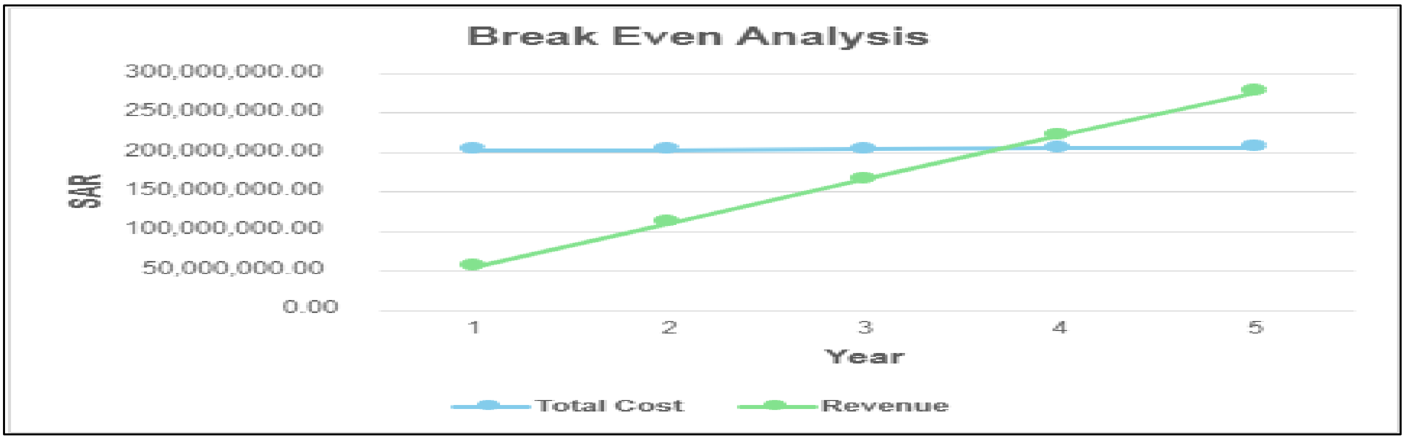

Fig 17 Break-Even Analysis

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According to the above graph, the Break-Even Point is reached in Year 4, when total revenue of SAR 222.14 million surpasses total costs of SAR 205.61 million. This milestone signifies the financial turning point for the vertical farming operation, where accumulated income starts to cover both the initial capital investment and ongoing operational expenses.

This analysis highlights the importance of distinguishing between fixed and variable costs and demonstrates how strategic financial planning and scaling production can lead to long-term viability. The cost and break-even insights provide a solid foundation for future decision-making regarding pricing, investment, and operational efficiency in vertical farming ventures.

C. Local and Global Levels

The selection of optimal locations for vertical farming in Saudi Arabia has significant implications at both local and global levels. Locally, identifying the best sites for vertical farms can enhance food security [56] by increasing lettuce production and reducing reliance on imports. Currently, Saudi Arabia imports a large quantity of lettuce, with Egypt being the top supplier at 70.3 million SAR worth of imports, followed by Spain at 33 million SAR and Jordan at 23 million SAR [57]. By establishing vertical farms in strategic locations, the country can reduce its dependency on imports and enhance domestic production. This contributes to Saudi Arabia's self-sufficiency goals while ensuring a stable supply of fresh produce.

On a global scale, optimizing vertical farm locations can position Saudi Arabia as a leader in sustainable agriculture, particularly in arid regions where water conservation is a priority. The adoption of advanced farming techniques may serve as a model for other nations facing similar environmental challenges.

D. Economic Implications

Various economic factors could be significantly influenced by the project. While vertical farming requires a higher initial investment compared to traditional farming methods, its strategic implementation can lead to long-term economic benefits [58]. Selecting optimal locations for vertical farms can enhance resource efficiency, increase profitability, and contribute to overall economic growth. In 2024, Saudi Arabia imported lettuce worth approximately 161.2 million SAR, while exports stood at only 4.8 million SAR, resulting in a negative trade balance of 156.4 million SAR [57]. Establishing local vertical farms can help reduce this trade deficit by increasing domestic production and decreasing reliance on imports. Additionally, Saudi Arabia's current lettuce production is about 13.7 thousand tons [57], which is not sufficient to meet domestic demand. Expanding vertical farming can boost local output, stabilize prices, and reduce fluctuations in supply. Furthermore, effective location planning encourages investment in agricultural technology, infrastructure, and workforce development, leading to job creation in both farming operations and related industries.

E. Enviromental Considerations

Vertical farming demonstrates significant environmental benefits, particularly in water conservation, as optimized location selection and closed-loop irrigation systems can reduce water usage by up to 90% compared to conventional agriculture, a critical advantage in arid regions like Saudi Arabia facing severe water scarcity [59]. Furthermore, the model promotes optimal land use and minimizes the environmental footprint by favoring sites with high land productivity and reducing pressure on arable land [60]. Moreover, proximity constraints ($\leq$ 200 km to urban markets) lower transportation-related emissions, enhancing urban food security while reducing greenhouse gas footprints [61] However, vertical farms generally have higher energy demands, integrating renewable energy sources, such as solar panels and wind turbines, can mitigate these costs and align the project with sustainable environmental practices [59,60]. Finally, urban-centric deployment fosters resilient food systems by shortening supply chains, minimizing food miles, and alleviating urban heat islands, thereby improving air quality and ensuring consistent fresh produce access [61]. Collectively, these outputs water and land efficiency, emission reductions, renewable energy synergy, and urban sustainability underscore vertical farming's dual economic and ecological viability, offering a scalable framework to address food security and environmental challenges in resource-constrained settings.

F. Societal Effects

Implementing vertical farming through optimized site selection in Saudi Arabia not only offers environmental and economic advantages but also generates significant societal benefits across multiple dimensions. Firstly, vertical farming enhances food security and local resilience by ensuring a steady, year-round supply of fresh produce, reducing dependency on imports and improving access to nutritious food in urban centers, particularly in regions with harsh climates like Saudi Arabia [59]. Secondly, it drives economic development and job creation by creating employment opportunities in construction, operations, and high-tech agriculture, while stimulating ancillary industries such as technology and logistics [60]. Thirdly, vertical farming promotes urban revitalization and social equity by repurposing underutilized spaces into productive hubs, ensuring fresh produce is accessible to all socio-economic groups and fostering healthier, more equitable communities [61]. Additionally, it positively impacts health and community well-being by providing nutrient-rich vegetables and integrating green spaces, which improve air quality, reduce stress, and enhance mental health. Lastly, vertical farming serves as a platform for educational and technological advancements, fostering research collaborations, skill development, and innovation in sustainable agriculture, thereby preparing future generations to address food security and environmental challenges effectively.

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VII. RESULTS AND DISCUSSION

This project aimed to develop a cost-effective, data-driven optimization model for the deployment of vertical farming systems across Saudi Arabia. The core objective was to minimize the total costs associated with establishing and operating these farms, while meeting urban demand for fresh produce in an efficient and sustainable manner. Using a MILP approach, the model integrates various factors such as land costs, infrastructure expenses, energy requirements, and water consumption to determine the optimal locations for vertical farms.

The model's success lies in its ability to provide a clear, quantifiable pathway for urban agriculture development, ensuring that farm locations are selected based on economic efficiency and their capacity to meet the urban food supply needs. It incorporates both fixed and variable costs, such as the initial setup costs for the infrastructure and land acquisition, alongside ongoing operational expenses like energy and water costs. Additionally, the model considers the amount of land available at each location and aligns this with the demand for lettuce in various cities.

The outcome of this project meets the needs of the stakeholders in urban food security, sustainability, and economic planning. The results enable decision-makers to evaluate where vertical farms can be most effectively placed, balancing the financial costs with the environmental and resource constraints of the region.

A. Alignment with Research Goals

The main customer requirement was to create an optimization tool that produces actionable insights for the strategic placement of vertical farms. This requirement was satisfied since the model provides a complete analysis of possible farm locations, as well as calculating the overall costs of each option. The model captures detailed data about each location, including but not limited to land costs, energy and water prices, that allow for careful decision-making aligned directly to customer requirements. Stakeholders can make decisions about where to invest in vertical farming to maximize efficiency and minimize costs and still achieve the goal of food security while mitigating sustainability.

The primary objective of minimizing the overall economic footprint of vertical farming operations was met through a carefully crafted objective function that incorporates key cost elements. The formulation of the cost structure, which includes fixed infrastructure costs, energy, and water expenses, allows the model to offer a clear path toward reducing total expenditures. Additionally, the project objectives were extended by integrating constraints that ensure farms meet the minimum production requirements for urban markets, thereby balancing cost minimization with the need to maintain adequate supply levels.

This model also fulfills the objective of helping urban agriculture meet food security challenges. By modeling the cost structure of vertical farms and making data-driven recommendations on farm locations, the model offers a solution that helps policymakers and industry leaders address the growing need for local, sustainable food sources.

Saudi Arabia faces the challenge of limited food resources due to the difficulty and high costs associated with traditional farming. Therefore, the focus of this research is on identifying the optimal locations for vertical farming to reduce resource usage while simultaneously increasing food production. This research focuses on selecting the best sites for vertical farming in five cities, aiming to minimize the use of resources such as cost and water while maximizing agricultural output. Through the developed optimization model, the research provides a data-supported methodology for site selection, contributing to the sustainability of vertical farming as a solution to the resource challenges in Saudi Arabia.

B. Recommendations

Due to the time limit of the research there are some limitations so here are some recommendations for future research: One area for improvement is the integration of transportation and logistics costs. The current version of the model emphasizes the production component of vertical farming by estimating the different costs of establishing and conducting farming operations. However, once the crops are produced, there are additional costs associated with transporting the produce from farms to urban centers where consumption occurs. Integrating transport and logistics costs would provide greater accuracy in describing the total cost profile. For instance, this could include models estimating the distance from various possible farm production sites to target cities, considering factors like fuel costs, vehicle maintenance, and distribution infrastructure. Consequently, the model could be more effective in capturing the full economic impact of the vertical farming sector.

Currently, the model focuses on a single crop, lettuce. To improve the versatility of the model, future work should extend the optimization framework to handle multiple crops with varying resource requirements. Each crop has varying needs in terms of water, energy, and space needs, and the ability to optimize across a range of crops would make the model more useful for broader agricultural planning. Furthermore, scalability should be considered; extending the model to different regions within Saudi Arabia or even other countries would help assess the feasibility of vertical farming in diverse climatic and economic contexts.

One of the key recommendations derived from this research is the decentralization of vertical farming using container-based farming units rather than fixed warehouse-style farms. By distributing smaller, mobile vertical farms across urban areas, fresh produce can be made more accessible to consumers while reducing the need for long transportation routes. These modular units can be placed in high-demand locations such as supermarkets and residential areas, ensuring a constant supply of fresh food while minimizing food miles and logistical inefficiencies.

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To address the high energy demands of vertical farms, renewable energy sources such as solar panels and wind turbines should be incorporated. Solar farms on rooftops or integrated wind turbines can help offset electricity costs and reduce the carbon footprint of VF operations. Saudi Arabia's abundant sunlight provides a strong case for solar energy as a primary power source for these farms.

With further advancements in AI, robotics, and automation, VF can evolve into highly self-sufficient farming systems requiring minimal human intervention. Automated harvesting and packaging systems will enable large-scale production with lower labor costs. Moreover, integrating IoT sensors can enhance real-time monitoring, ensuring precise control over every aspect of the farming environment.

One key recommendation is to establish partnerships with agricultural institutions, local government bodies, or private vertical farming companies to gain access to real-world data. Such collaboration would enhance the accuracy and reliability of the model by incorporating actual operating costs, crop yields, water usage, and energy consumption specific to different regions. Real-time and localized data would help address variations caused by environmental conditions, infrastructure availability, and market dynamics factors that are often difficult to capture through theoretical assumptions alone. This kind of data-driven refinement would make the model more grounded, adaptable, and valuable for real-world implementation.

By implementing these recommendations, vertical farming in Saudi Arabia can transition from a niche agricultural practice to a mainstream, sustainable solution for food security. Through continued innovation and strategic investment, VF has the potential to revolutionize urban agriculture and play a crucial role in the nation's long-term food sustainability goals.

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