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Review

Sustainable and Low-Input Techniques in Mediterranean Greenhouse Vegetable Production

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Abstract: In the modern agricultural landscape, numerous challenges, such as climate change, diminishing arable lands, and the reduction of water resources, represent significant threats. The Mediterranean greenhouse farming model relies on low-input strategies to maximize both yield and quality. Its protected horticulture is essential for the year-round cultivation of high-value crops, ensuring efficient and sustainable production. In the realm of future agricultural strategies, leveraging internet-based approaches emerges as a pivotal factor for real-time and remote control of various agricultural parameters crucial for crop growth and development. This approach has the potential to significantly optimize agronomic inputs, thereby enhancing the efficiency of targeted vegetable production. The aim of the present review is to underscore the challenges related to the intensive greenhouse production systems emphasizing various strategies leading to low-input greenhouse vegetable production. The goal is to promote more sustainable and resource-efficient approaches in the cultivation of greenhouse vegetables. This review highlights several key strategies for optimizing the greenhouse environment, including efficient water management through conservation tillage, drainage water reuse, and selecting the most appropriate irrigation systems and timing. Additionally, light modulation and temperature control—using solar energy for heating and pad-and-fan systems for cooling—are crucial for enhancing both crop performance and resource efficiency. The review also explores low-input agronomical strategies, such as pest and disease control—including solarization and optimized integrated pest management (IPM)—as well as fertilization and advanced growing techniques. These approaches are essential for sustainable greenhouse farming.

Keywords: environmental sustainability; greenhouse farming; protected plant cultivation

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1. Introduction

Protected cultivation has quickly spread to many parts of the world, particularly in the Mediterranean regions characterized by mild winter climates. Consequently, the greenhouse industry is persistently innovating and creating new technologies to address specific cultivation issues, reduce environmental impact, and meet changing market needs [1,2]. Both industry experts and researchers have made considerable strides in innovation and research. Their work focuses on cutting production costs and decreasing the environmental footprint of state-of-the-art greenhouse technologies, all while satisfying consumer demands [3]. Within this context, smart greenhouse systems target energy, chemical, and water inputs. Advanced decision support systems and technologies, such as climate control equipment and sensors, reduce energy use, emissions, and external climate impact. Soilless cultivation and moisture sensors optimize water and fertilizer management, enhancing sustainability and efficiency [2,4–6]. Over the previous decades, the use of chemical fertilizers and pesticides has significantly boosted crop yields globally. Nevertheless, the impact of intensive use of these agrochemicals on the long-term sustainability of this approach has grown due to their adverse effects on human health, biodiversity, and the environment [4,7,8]. Therefore, there is an immediate need to advance crop protection science to address the comprehensive challenges facing 21st-century agriculture, including sustaining or enhancing productivity, producing nutritious food, mitigating agriculture's negative impacts on ecosystems and human health, ensuring the economic viability of farms, and adapting to climate change [4]. These strategies necessitate a thorough evaluation of viable low-input technologies designed to minimize the adverse impacts of agricultural production.

Greenhouse cultivation offers numerous advantages for vegetable production, enhancing both the quantity and quality of yields. The controlled environment within greenhouses allows for precise regulation of temperature, humidity, and light, providing optimal conditions for plant growth throughout the year. This results in accelerated crop development, extended growing seasons, and higher yields compared to traditional open-field farming. Additionally, greenhouse farming facilitates the cultivation of vegetables in regions with adverse weather conditions or limited arable land, promoting agricultural sustainability and food security on a global scale.

Throughout the historic evolution of protected cultivation strategies, a primary objective has been the optimization of costs associated with plant cultivation within controlled environments. Modern greenhouse design underscores the efficient utilization of space and the selection of materials that effectively preserve environmental conditions within the cultivation area, minimizing energy wastage [9,10]. Greenhouses are designed to optimize the utilization of solar radiation energy, a pivotal input for plant growth. Technological advancements, including precision agriculture, automated climate control, and innovative irrigation, have improved growing conditions, resource efficiency, and sustainability [11]. By leveraging these advancements, greenhouse farmers are able to optimize growing conditions, enhance resource efficiency, and minimize environmental impacts [12,13]. Crop simulation models optimize costs by predicting agricultural outcomes under changing climates. Life-cycle assessment (LCA) evaluates the environmental impacts of a product or process throughout its entire life cycle, from raw material extraction to disposal [14,15]. Within this scenario, technological advancements like big data, robotics, and AI have revolutionized agriculture, enhancing greenhouse productivity and sustainability. However, in the Mediterranean region, implementation is hindered by high costs, small farm sizes, and an aging, less-educated farmer population [16]. These technological interventions not only correct potential drawbacks but also enable the sustainable expansion of greenhouse farming, fostering a more resilient and productive agricultural sector. This progress is further supported by young graduates returning to agriculture, who are more open to training and innovation, potentially lowering costs and accelerating the adoption of these technologies in the future [16].

We underscore that in the realm of low-input strategies and the future of agriculture, greenhouse structures, precision agriculture, automated climate control, and innovative irrigation systems work together to boost resource efficiency and sustainability. Precision agriculture and automated climate control fine-tune environmental conditions and resource use, while advanced irrigation systems reduce water waste. Crop simulation models offer valuable insights for optimizing these practices, and LCA measures their overall environmental impact. Combined, these technologies pave the way for more efficient, sustainable, and resilient agricultural systems.

Within this framework, Low-Input Sustainable Agriculture (LISA) stands out as a farming system capable of producing food and fiber continuously and profitably while preserving the integrity of natural resources [17]. By prioritizing safe practices and reducing reliance on external inputs, LISA aims to ensure the supply of nutritious foods and minimize health risks. This approach emphasizes utilizing on-farm resources to promote self-sufficiency and minimize environmental impact, fostering a resilient and sustainable agricultural system [17].

The intricate relationship between agricultural prices and geopolitical scenarios is evident as conflicts or tensions in key agricultural regions can disrupt supply chains, leading to price volatility. Geopolitical events such as trade disputes or sanctions can impact market dynamics, affecting commodity prices and food security worldwide. The interplay between geopolitical tensions and agricultural markets underscores the need for resilience and adaptive strategies in the face of global uncertainties [18].

The current review aims to provide insights into modern greenhouse vegetable production, with a specific focus on methods and strategies for achieving sustainable vegetable production with minimal inputs. Figure 1 depicts the structure of the present review, highlighting the intricate relationship between greenhouse environment and agricultural practices.

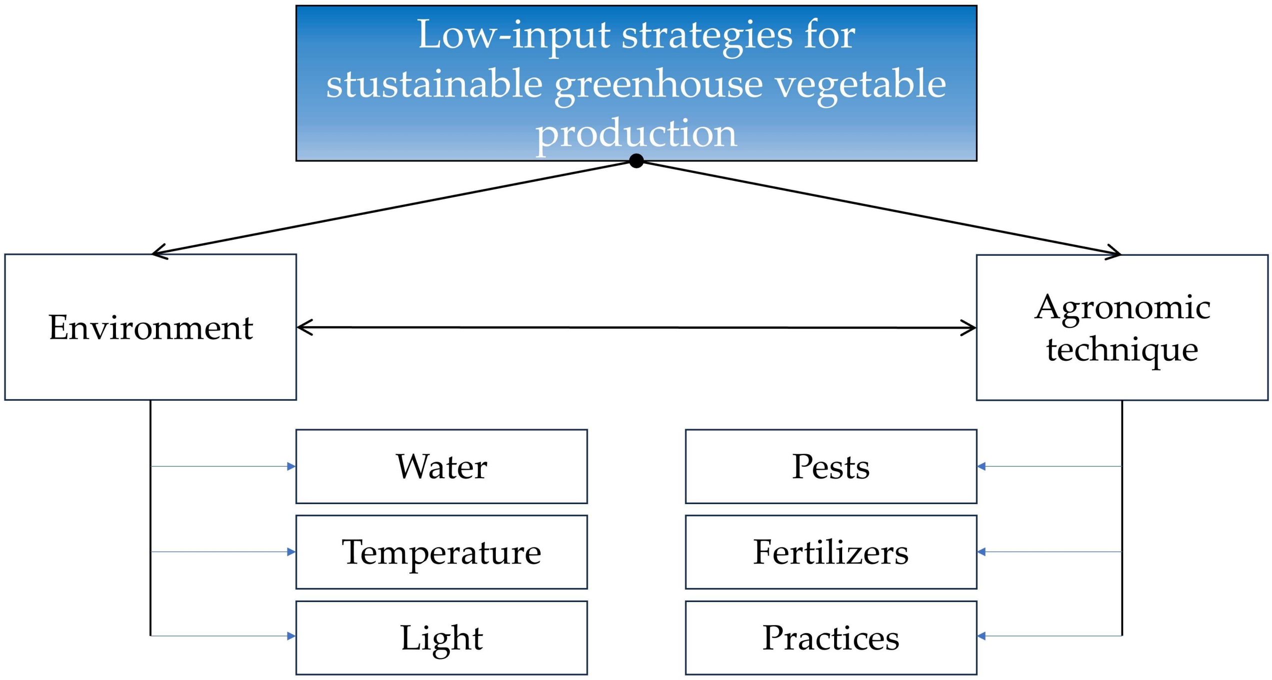

Figure 1. Schematic graphical representation of the various points discussed in the present review. It is worth mentioning the intricate relationship between environmental conditions and agricultural practices.

Initially, the primary focus of most studies was on increasing production and reducing costs. However, there has been a significant shift towards prioritizing more sustainable systems from economic, social, and environmental perspectives. This change is driven by various factors, including the rising demand for ecologically and sustainably produced goods, increased awareness among stakeholders about environmental issues, international regulatory changes aimed at environmental conservation and clean production, and the growing recognition of the impacts of climate change on the agricultural sector.

2. Different Set-Up of the Modern Greenhouses

Greenhouses prove highly effective in producing high-value crops, utilizing natural resources and production inputs efficiently. As a result, these structures have a significant global presence, covering extensive areas worldwide [19]. Greenhouse designs encompass various pertinent production systems, including low-tech greenhouses and high-tech greenhouses [20–23]. The broad array of greenhouse design solutions may be categorized basing on shape, utility, construction, and covering materials. It is important to note that there is not a singular "best" type; rather, each greenhouse solution offers advantages tailored to specific applications. Various greenhouses are adept at meeting the unique requirements of different agricultural systems The exploration of these facets contributes valuable insights into optimizing greenhouse environments for effective and sustainable agricultural practices [23]. Greenhouse technology serves as a valuable tool for enhancing crop yields by precisely adjusting internal climate growth conditions, including temperature, humidity, light intensity, and CO_2 concentration.

The structural design of agricultural greenhouses poses a challenge for designers seeking to align with economic conditions. The greenhouse geometry, such as aspect ratio and roof shape, significantly influences the microclimate, growing conditions, and energy consumption [10].

As highlighted in a previous work [23], considerations such as shape, orientation, ventilation systems, and heating/cooling systems are crucial factors to be considered in greenhouse design. The orientation and roof shape impact solar gain, with solar gain increasing linearly with roof angle. Greenhouses can be categorized into multiple gutter-connected and stand-alone types, and their orientation plays a crucial role in overall thermal performance, affecting exposure to solar radiation. Greenhouse covers, including glass, rigid plastics, and thin plastics, contribute to creating a controlled environment. Ventilation is essential for optimizing crop yields, managing parameters like temperature, humidity, and CO_2 levels. The choice of cover material for greenhouses is influenced by the specific growing environment. Conventional single-sheet glass, while valued for its high light transmittance, durability, and cost-effectiveness, suffers from brittleness and heaviness, which can affect structural integrity and handling. In contrast, plastic covers are increasingly favored for their versatility and lower cost, offering practical advantages for modern greenhouse applications [24]. Shading complements ventilation to reduce solar radiation intensity, particularly in hot regions, influencing microclimate and crop productivity. Various shading levels have been explored for their effects on greenhouse microclimate and crop responses [20]. The drawbacks of shading systems vary based on the specific environmental conditions of an area and the methods used. For example, shading systems that employ curtains or screens below the greenhouse roof can reduce ventilation effectiveness when fully deployed. This can adversely impact the greenhouse microclimate, particularly in regions with high humidity where adequate ventilation is crucial [25].

It is noteworthy to highlight that the considerable upfront expenses associated with greenhouse technology pose a major obstacle to its adoption among farmers. Over time, numerous scientists and engineers have contributed efforts to lower the technology's costs, often achieved through the utilization of alternative construction materials or the implementation of inventive environmental control techniques [26]. When selecting alternative materials for agricultural use, it is crucial to ensure they provide adequate protection for crops against natural calamities, such as strong winds. These materials should be robust and resilient, capable of withstanding harsh weather conditions to prevent damage to the crops. Effective wind protection can minimize crop loss and improve overall agricultural productivity, making it an essential consideration in the choice of materials [16,26,27].

The improvement of greenhouse technology holds substantial potential for cost and input optimization. To achieve this goal, various web-based tools and electronic platforms have been created for real-time monitoring and remote control of agricultural parameters. This approach aligns with the Agriculture 4.0 perspective and is expected to be further explored and utilized in the coming years [28,29]. Effective control of environmental factors is essential for significant cost savings, ensuring optimal growth conditions for crops, and extending the production season to maximize yields. Employing a cost-effective data transmitter, like a chip integrated within sensors, for agricultural data transmission in the network layer offers an affordable gateway solution, ensuring the secure flow of data on the Internet of Agriculture.

Greenhouse designs encompass various production systems, including low-tech Mediterranean greenhouses—originally low-input but now enhanced with modern technologies—high-tech greenhouses, and the innovative Chinese solar greenhouse (CSG) [30,31]. Mediterranean greenhouses stand out due to their unique characteristics and advantages. These greenhouses are designed to take advantage of the region's mild winter temperatures, enabling vegetable production with minimal heating costs [32]. Typically, they consist of simple structures covered with plastic film, lacking the fixed installations required for winter heating found in more technologically advanced greenhouses. Over the past decades, this low-tech approach to protected horticulture has driven economic development in several marginalized and impoverished regions by providing a cost-effective means of year-round vegetable production. These growing areas are often located near the sea, taking advantage of the favorable coastal climate to further reduce heating needs and optimize growing conditions (Figure 2).

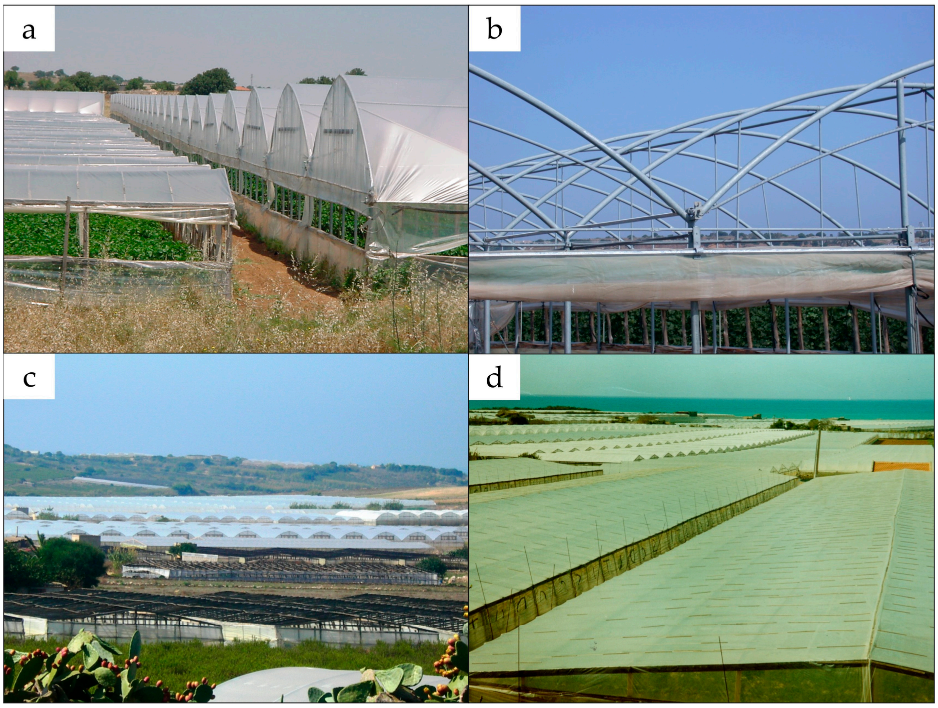

Figure 2. Typical Mediterranean greenhouses in Sicily, particularly in the Ragusa (RG) province, showcase semi-closed structures covered with plastic films, usually characterized by low height (**a**,**b**). The horticultural area of Ragusa is seamlessly integrated into the agricultural landscape, as seen in the typical Sicilian scenery (**c**). Additionally, greenhouse systems are often situated adjacent to the Mediterranean Sea, optimizing coastal climate benefits (**d**). All images are credited to the authors.

In the Mediterranean region, utilizing a unified greenhouse structure for various crops is both cost-effective and practical, given the region's consistent environmental conditions. This approach offers flexibility in crop rotation and scalability, significantly reducing construction and maintenance costs. While the physical structure remains the same, it is essential to tailor control systems and agricultural practices to meet each crop's specific requirements, including irrigation, pruning, fertilization, and phytosanitary treatments. By integrating smart technologies, these customized systems can efficiently address the diverse needs of different crops within the same greenhouse, promoting sustainable and productive farming.

While Mediterranean greenhouses leverage mild winters and high solar radiation for year-round production, the CSG is a major advancement in energy efficiency, designed to retain heat and reduce the need for artificial heating, adopting renewable sources of energy. With a south-facing transparent wall and insulated back wall, it captures solar energy effectively [33–35]. Recent innovations, such as photovoltaic (PV) greenhouses and improved thermal storage, have further enhanced energy efficiency, positioning China as a leader in sustainable greenhouse technology. While the CSG is a promising model, this review focuses on the Mediterranean greenhouse, which remains a crucial solution for horticultural production in the Mediterranean region.

3. Impact of "Conventional" Greenhouses in Modern Agriculture

According to the Food and Agriculture Organization (FAO), the European Union has approximately 405,000 hectares of greenhouse space, which includes both glass- and plastic-covered structures [36]. Conventional intensive greenhouses have a significant impact on both costs and the environment. Economically, they require substantial investments in infrastructure, energy, and water. As outlined, irrigation and fertilization are the largest consumers of energy, with usage ranging from 1 to 19% for irrigation and 1 to 27% for fertilization [36]. The costs associated with heating, cooling, and maintaining optimal growing conditions can be high, particularly in regions with extreme weather conditions [37–39]. Environmentally, conventional greenhouses often rely on fossil fuels for energy, leading to greenhouse gas emissions and contributing to climate change. As documented, integrating agrivoltaic (APV) systems into greenhouse farming can generate up to 200 kWh m^{-2} of energy annually without impacting crop growth. This is particularly advantageous for regions with high light intensity [40].

Additionally, the use of chemical fertilizers and pesticides in these systems can result in soil degradation, water pollution, and harm to beneficial insect populations. However, advancements in greenhouse technologies, such as improved climate control systems, renewable energy sources, precision agriculture, and sustainable farming practices, are being developed to mitigate these impacts [39].

For instance, as documented, the precision agriculture market is expected to grow at a rate of 15% annually, reaching over USD 12 billion by 2025, driven by advances in smart technologies and renewable energy integration [41]. Managed precision agriculture services are projected to grow at a rate exceeding 27% during the same period.

Among the various strategies that can be employed to promote sustainable and high-quality agricultural production, soilless systems such as hydroponics and aquaponics offer significant advantages over conventional greenhouse farming [42–45]. These systems optimize water usage by recycling it within closed loops, significantly reducing water waste and the need for chemical inputs. Additionally, soilless cultivation prevents soil degradation and reduces the risk of soilborne diseases, making it a more sustainable alternative. Another modern approach to greenhouse farming that ensures sustainable production is vertical farming, which maximizes space efficiency by allowing multiple layers of crops to be grown in the same area [46,47]. This approach not only increases yield per square meter but also reduces the overall resource footprint, offering an innovative solution to meet the demands of a growing population while minimizing environmental impact. As outlined, lettuce is a key crop for both hydroponic and aquaponic purposes [48,49]. Aquaponics is a sustainable farming method that integrates fish cultivation (aquaculture) with plant growth in a water-based system (hydroponics). Fish waste provides nutrients for plants, while plants filter and purify the water for the fish, creating a closed-loop system that conserves water and reduces the need for chemical fertilizers [50].

By adopting these innovations, it is possible to reduce operational costs and minimize environmental footprints, making greenhouse agriculture more sustainable in the long run [39].

As documented, the environmental impact varies depending on the crop and the growing techniques employed [51]. For instance, as outlined in a previous study, the cultivation of tomatoes exhibited a lower environmental footprint compared to cucumber (*Cucumis sativus* L.) cultivation [52]. This was attributed to reduced total energy input, resulting in lower environmental burdens across all impact categories. Notably, the dominant contributors to almost all impact categories were identified as natural gas, electricity, and nylon (used as a greenhouse cover material) [52].

Agricultural practices exert notable effects on soil properties and microbial communities, with limited understanding of their responses in both open field and greenhouse settings under organic and conventional management. As previously documented by a genetic assessment study of the soil microbial community, organic farming in plastic tunnels significantly enhanced soil nutrients, particularly available N and P, by 137% and 711%, respectively, compared to conventional farming [53]. This method also increased microbial abundance and diversity, improving soil fertility and microbial dynamics [53]. Furthermore, organic management practices increased total nematode abundance, especially bacterivores, fungivores, and omnivore–carnivores, compared to low-input and conventional methods [54]. This aspect can be attributed to the increased soil food complexity and web and its higher biomass in comparison to conventional farming. In fact, the heightened biomass in organic systems was particularly noticeable at elevated trophic levels [54].

Nevertheless, it is worth noting that conventional greenhouses are a vital component of modern agriculture. They provide controlled environments that enhance crop production efficiency and quality, ensuring a high supply of food resources. In conclusion, conventional greenhouses have a significant impact on modern agriculture by improving crop yield, resource efficiency, and soil health. While energy consumption in greenhouse cultivation poses various challenges, technological advancements and sustainable practices are mitigating these issues. The primary obstacles for energy-efficient systems include high initial costs and variable effectiveness depending on local climate conditions and greenhouse design. Advancements in smart energy management systems and renewable energy integration, like solar panels, promise to further decrease energy costs and improve sustainability [36]. Furthermore, the controlled environment of greenhouses allows for innovative climate management and pest control strategies, contributing to the overall sustainability and productivity of agricultural systems. Currently, integrated pest management (IPM) strategies, which include biological control and targeted pesticide use, effectively manage pest populations while minimizing chemical use and environmental impact. However, implementing IPM requires continuous monitoring and can vary in effectiveness based on pest species and greenhouse conditions. Future improvements could come from advances in pest-resistant plant varieties, more effective biopesticides, and enhanced predictive models for pest outbreaks, all of which could streamline and strengthen IPM practices.

Ongoing research and development will continue to enhance the benefits and reduce the environmental footprint of greenhouse agriculture.

4. Optimizing the Greenhouse Environment Using Low-Input Strategies

4.1. Greenhouse Environment

Greenhouse technology provides a versatile and sustainable year-round solution for cultivating a variety of vegetable crops, particularly in challenging climates or resource-constrained areas. To improve cost-effectiveness and competitiveness, it is crucial to comprehend plant needs throughout growth stages and diverse light conditions, facilitating the design of adaptive control strategies. The scientific literature provides a range of recommendations for optimal microclimate parameters at different growth stages for the most commonly cultivated greenhouse vegetables in the Mediterranean basin, including tomatoes (*S. lycopersicum* L.), zucchini (*Cucurbita pepo* L.), eggplants (*S. melongena* L.), sweet peppers (*Capsicum annuum* L.), and cucumbers (*Cucumis sativus* L.) [55–57].

Given the impact of heating on greenhouse yield, quality, and cultivation time, attention has shifted toward alternative energy sources due to the high cost and uncertain availability of fossil fuels. Solar energy emerges as an attractive substitute for both passive and active greenhouse heating. By capturing and storing solar thermal energy—whether as sensible heat, latent heat, or through chemical reactions—greenhouses can achieve sustainable heating without relying on costly conventional fuels [58]. The potential cost reduction for energy required in greenhouse heating and cooling across southern European and Mediterranean regions can be achieved by adopting renewable energy sources. Additionally, this study examines the potential reduction in carbon footprint associated with renewables compared to conventional energy sources [59].

In Mediterranean greenhouses, heating systems are typically unnecessary except in rare cases. Indeed, within the Mediterranean greenhouse production system, cost-effectiveness takes precedence due to limited climate control. Consequently, occasional suboptimal greenhouse climates lead to suboptimal crop yields [30,60]. However, well-designed and efficiently operated Mediterranean greenhouses strike a positive economic balance between agronomic performance and the relatively low investment and operational costs [61]. However, optimizing heating conditions remains a priority for cost-effectiveness. Solar thermal, biomass, and absorption heat pump technologies offer viable options for actively managing greenhouse climate conditions. By harnessing solar thermal and biomass energies, it is possible to minimize natural resource consumption and waste generation [62,63]. A system that integrates solar collectors, a biomass boiler, and an absorption chiller was recently proposed [64]. In the Almeria region, a hybrid passive cooling and heating system was specifically developed for Mediterranean greenhouses cultivating sweet peppers [65]. Remarkably, this system led to a substantial increase in marketable yield—approximately 25%. This boost in yield not only enhances productivity but also contributes to cost optimization. Specifically designed for a tomato crop greenhouse in Almeria, this system addresses both heating and cooling demands.

To achieve energy-saving production in high-temperature and high-humidity climates, particularly in Mediterranean greenhouses, several strategies can be employed. In fact, in high-temperature and high-humidity climates, Mediterranean greenhouses can achieve energy-saving production by leveraging natural heat to reduce winter heating needs and integrating solar panels to power greenhouse systems [58,66]. Effective humidity management through optimized ventilation and passive cooling techniques can further enhance efficiency, minimizing the reliance on external energy sources while maintaining optimal growing conditions. A practical example of such efficiency is the use of heat pumps for dehumidification in closed tunnel greenhouses, which are widely employed in Mediterranean protected horticulture [67,68]. These systems manage high relative humidity by cooling the air to condense moisture and then reheating it before returning it to the greenhouse. Monitoring parameters such as the coefficient of performance (COP) and specific energy consumption (SEC) demonstrates how Mediterranean greenhouses can maintain optimal conditions while improving energy efficiency. Additionally, natural ventilation can significantly enhance climate control and reduce energy consumption [69,70]. By optimizing the placement and number of vents—using a combination of roof and side vents—greenhouses can take advantage of prevailing winds and temperature differentials to promote efficient air exchange. Computational models are crucial in developing the best natural ventilation solutions, as they enable precise simulations and adjustments to achieve optimal airflow and climate conditions. This approach not only helps maintain ideal temperature and humidity levels but also reduces reliance on mechanical cooling and ventilation systems, contributing to a more sustainable and cost-effective greenhouse environment. Together, these methods make Mediterranean greenhouses a viable solution for energy-efficient horticulture in challenging climates.

Accurate crop evapotranspiration estimation depends on aerodynamic and canopy resistances, which are directly influenced by the greenhouse covering materials. In fact, different covering materials affect the internal microclimate by altering solar radiation, humidity, and temperature, all of which impact evapotranspiration rates [71–73]. The analytical model for calculating these values within greenhouses can significantly improve water management and climate control systems in Mediterranean greenhouses [74]. The choice of greenhouse cover material plays a crucial role in shaping the internal environment. Each material exhibits distinct physical and chemical properties, which must be carefully considered in light of both the external greenhouse conditions and the associated costs [27,75]. Within this context, Figure 3 provides a graphical representation of the average costs of the petrochemicals, plant, and mixed greenhouse cover materials.

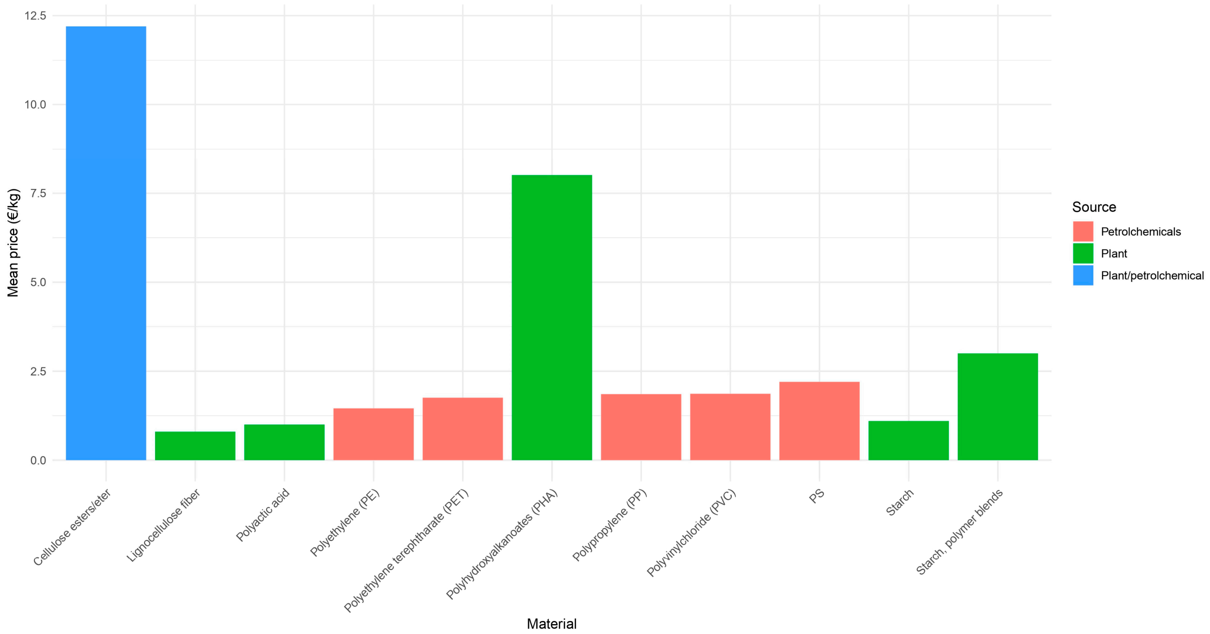

Figure 3. A bar plot related to the mean price (€/kg) related to the greenhouse cover material. The data employed were taken from a previous study [75]. The bar plot was generated using R studio version 3.4.3. with the package ggplot2.

Bioplastics are slightly expensive compared to petroleum-based plastics; it costs between €0.77–0.81 to manufacture petroleum-based plastics such as polyvinyl chloride (PVC), polypropylene (PP), polyethylene terephthalate (PET), thermal polyethylene film (TPE), ethylene–vinyl acetate film (EVA), and three-layer co-extruded film (3L) [75]. In contrast, it costs up to €12.00/kg to manufacture polyhydroxyalkanoates (PHAs). Therefore, polylactic acid (PLA) and PHA plastic films are not suitable from an economic perspective. However, the higher costs are offset by ideal material properties such as elongation at break, tensile strength, and the glass transition temperature, as illustrated in Table 1. From another perspective, the cost factors can be resolved through research and development and synthesis of new materials. Table 1 describes the variation of the thermal and mechanical parameters of plant-based and petroleum-based polymers, according to previous studies [27,75].

Table 1. Variation of the thermal and mechanical parameters of plant-based and petroleum-based polymers, according to previous studies [27,75]. The parameters described were the tensile strength (TS), the elongation at break (EB), the glass transition temperature (GTT), and the melting temperature (MT).

Material	TS (MPa)	EB (%)	GTT (°C)	MT (°C)
Kraft paper	68	3		
Cellulose acetate	90	25	110	230
Corn starch	40	9	112	
PLA	59	2–7	55	165
PHA	15–50	1–800	12–3	100–175
PBS	34	560	−32	114
PBAT	22	800	−29	110
PEF	35–67	3–4	85	211
PTT	49	160	50	228
PE	15–30	1000	−125	110–130
PP	36	400	−13	176
PET	86	20	72	265
PS	30–60	1–5	100	–
PVC	52	35	−18	200

4.2. Low-Input Strategies for Optimizing Water Management

Effective water management in greenhouses is crucial for enhancing efficiency and minimizing costs. By optimizing irrigation practices, growers can ensure that plants receive the precise amount of water needed for optimal growth, thereby reducing water waste. Advanced technologies such as drip irrigation and soil moisture sensors allow for precise control over water distribution, preventing over-irrigation and nutrient leaching. This not only conserves water resources but also reduces energy and fertilizer costs, ultimately leading to more sustainable and cost-effective greenhouse operations. Implementing proper water management strategies is essential for achieving high productivity while maintaining environmental and economic sustainability [76–78].

The introduction of water resource-conserving technologies (RCTs) in the existing cropping system will boost the resource or input use efficiency by establishing the crops on time; saving the requirements of water, fuel, and labor; reducing the production costs; improving yields; and mitigating the GHG emissions [79]. The significant benefits of conservation tillage practices aimed at conserving water resources and minimizing losses include maintaining soil structure (aggregation), enhancing soil organic carbon, reducing soil erosion risks, conserving soil moisture, stabilizing soil temperature fluctuations, and improving overall soil quality [17,80].

The retention of water in the growing substrate and its subsequent uptake by plants can be influenced by the type of substrate utilized. For instance, as demonstrated in greenhouse tomato cultivation, the selection of an appropriate substrate can exert a significant impact on various attributes associated with the marketable yield [81]. According to a previous study, smart irrigation practices reduce water and energy use by 38.2%, providing environmental benefits of up to 62% and life cycle benefits of 13% per ton of product. Despite initial costs, these practices enhance water–energy efficiency, proving economically advantageous and environmentally sustainable for Mediterranean greenhouse cultivation [82].

As documented, reusing drainage water in greenhouses can cut water and fertilizer use by 20% and reduce freshwater consumption and marine eutrophication by over 50% [83]. These strategies are financially viable, with a net present value greater than €400,000 over 20 years. Furthermore, avoiding substrate landfilling boosts profitability. Eco-efficient methods such as cascade cropping, and closed-loop fertigation are key to optimizing resource use and supporting sustainability [83].

Another factor that influences the irrigation management and agricultural costs is the timing of irrigation. In fact, irrigation timing refers to the strategic scheduling of water application to crops based on their needs and environmental factors. Proper timing optimizes water use, enhances crop yield, and reduces water waste and costs [84,85]. Additionally, the timing of water application significantly influences plant growth and ion uptake [86]. As documented, applying 60–70 mm of irrigation water after cropping effectively lowers soil salinity, facilitates replanting, and reduces fertilizer costs by optimizing water and nutrient application. This method also necessitates affordable, efficient monitoring systems to maximize effectiveness [87].

In the Mediterranean basin, numerous regions experience semi-arid conditions, driven by the scarcity of water resources. This limited availability of water poses significant challenges for agriculture, making the selection of an appropriate irrigation system essential. Choosing the right irrigation system is crucial not only for optimizing water use but also for enhancing crop productivity and sustainability. Effective irrigation practices can help mitigate the effects of water scarcity, improve soil health, and ensure that crops receive adequate moisture throughout their growth cycles. As water resources become increasingly constrained, adopting advanced and efficient irrigation technologies becomes even more vital to address the dual pressures of limited water availability and the need for sustainable agricultural practices [32,88]. For instance, according to recent studies, southern Italy, a key region for greenhouse vegetable production, is currently facing a significant increase in drought events due to climate change [89,90]. For example, a report by the Sicilian region indicates that in 2024, Sicily is experiencing severe drought conditions, which will undoubtedly impose constraints on Sicilian agriculture. Available online: https://www.regione.sicilia.it/ (accessed on 10 August 2024).

Many growers have adopted technological improvements in irrigation and water-saving practices. However, adoption remains low due to high costs and the lack of direct financial benefits from water conservation. Additionally, inadequate internal climate control and insufficient water and nutrient supply in protected cropping systems lead to increased biotic and abiotic stresses, which adversely impacts yield [91]. In this context, advancing technologies are focused on developing cost-effective precision irrigation systems, such as soil moisture sensors and automated controls, to enhance water efficiency and lower operational costs.

To ensure food production in semi-arid Mediterranean regions amidst water scarcity and economic constraints, optimizing irrigation and fertigation is crucial. This requires tailoring practices to specific greenhouse microclimates for efficient water and fertilizer use. Implementing precision agriculture techniques, such as nutrient uptake modeling and smart technologies, is essential, though many recommended practices may not be suitable for Mediterranean climates, as they often stem from northern European conditions [91].

4.3. Low-Input Strategies for Light Modulation

Efficient light utilization is crucial for the development of greenhouse crops, particularly in Mediterranean regions. This efficiency is closely tied to the selection of suitable film cover materials that enhance light transmittance and increase the proportion of diffuse light, thereby promoting a more uniform light distribution [92]. In fact, implementing energy-efficient lighting systems and optimizing canopy photon capture are effective money-saving techniques for modulating light inside greenhouses during vegetable cultivation. These strategies help minimize operational costs while maximizing light utilization for optimal plant growth [93]. Ground albedo, a critical component of solar radiation, plays a vital role in the interaction between ground surfaces and canopy architecture in capturing solar radiation inside Mediterranean greenhouses. It significantly impacts both incident and reflected solar radiation on the ground surface and the greenhouse roof cover. Plastic and gravel-sand mulches notably influence the ground and cover albedo of greenhouse crops. Expanding Mediterranean greenhouse areas could increase the global albedo regionally [94].

Various renewable and sustainable technologies, including photovoltaic modules, solar thermal collectors, phase change materials, energy-efficient heat pumps, and innovative ventilation and lighting systems, can significantly enhance energy savings in greenhouse operations. Research indicates that implementing these technologies can lead to up to 80% energy savings, with a payback period ranging from 4 to 8 years, contingent upon climatic conditions and crop type [95]. Mediterranean greenhouses, utilizing simple plastic-covered structures without fixed winter heating, leverage the region's high solar radiation. Unlike central and northern European greenhouses, they rely on favorable climatic conditions. However, photovoltaic greenhouses with opaque south-facing panels limit and unevenly distribute solar radiation, impacting the ability to grow plants in protected environments [96,97].

The optimization of light use efficiency (LUE) offers a significant opportunity to enhance agricultural productivity. By maximizing the amount of light energy converted into plant biomass, growers can achieve higher yields with the same or even reduced input levels. This approach not only boosts crop production but also contributes to sustainable farming practices by improving resource use efficiency [98–100]. Enhanced LUE can be achieved through various methods, such as selecting crop varieties with higher photosynthetic efficiency, optimizing planting density, and using advanced technologies like supplemental lighting and reflective mulches to increase light availability and distribution within the crop canopy [101–104].

The modulation of solar radiation within the greenhouse environment greatly hinges on the quality of the cover material used. Furthermore, the positioning of the greenhouse plays a critical role in determining the quantity of photons reaching inside. Therefore, selecting the appropriate greenhouse design is a crucial decision prior to commencing vegetable cultivation, ensuring both sustainability and cost-effectiveness in production. Within this context, sun exposure can significantly change the climatic conditions inside the greenhouse environment [105,106]. The development of a sunlight prediction method using a time-variant Markov model has led to an optimal, prediction-based supplemental lighting approach for greenhouses. The generation of an effective model minimizes lighting costs, achieving up to 45% savings in supplemental lighting electricity over a year [107]. A study conducted in Murcia, Spain, assessed tomato yields using recent price data. The highest annualized economic values were obtained with UVA100%e covers (€24,856.04/year), followed by UV90%e and PeTc. In contrast, LDe and Anti NIR covers produced the lowest economic returns (€3954.93 and €10,480.40 per year, respectively) [108].

Currently, various strategies linked to the photoperiod can be adopted to increase the yield of many crops, such as tomatoes. Supplemental LED lighting has been shown to significantly boost tomato yields in Mediterranean greenhouses. This has been evaluated in different greenhouse systems, including closed, semi-closed, and hydroponic setups [109–111]. It is important to note that these solutions require substantial capital investment. However, they enable yield maximization, extend the growing season, and ultimately increase revenues. A study comparing LED and HPS lighting in greenhouses found that the most cost-effective approach combines efficient lighting fixtures with effective canopy photon capture, optimizing photon delivery and reducing overall system costs [112].

4.4. Low-Input Strategies for Controlling Temperature

Controlling temperature in Mediterranean greenhouses is crucial for optimizing crop yields while adhering to low-input agricultural practices. Given the region’s hot and variable climate, effective temperature management ensures that crops receive consistent conditions conducive to growth without the need for excessive energy inputs. By employing strategies such as passive cooling, natural ventilation, and thermal mass, growers can minimize reliance on high-cost energy solutions, reduce operational expenses, and maintain a sustainable balance between production efficiency and environmental impact [113,114]. This approach supports the goals of low-input agriculture by enhancing resource use efficiency and reducing the overall carbon footprint of greenhouse operations.

The potential for energy savings through various design parameters, such as greenhouse shape and orientation, is highly dependent on the specific location. In colder regions, the effectiveness of passive heating systems like water tanks and rock beds may be limited for commercial greenhouse operations. As alternatives, utilizing industrial waste heat, geothermal energy, and wood biomass presents viable options for reducing heating costs in large-scale greenhouse production [10]. Furthermore, reducing heating costs is a major challenge for greenhouses growers, especially those located in cold regions. Several techniques have been applied to reduce greenhouse heating costs in winter [10,115].

Nowadays, advancements in virtual prediction greenhouse models have allowed for detailed analysis of the greenhouse microclimate [116,117]. For instance, Computational Fluid Dynamics (CFD) models are often employed to analyze the leaf boundary layer microclimate in greenhouse crops. This analysis is crucial for targeted pest control and sustainable production. CFD models enable the deduction of air temperature and humidity profiles within the leaf boundary layer, contributing to innovative climate management strategies [116,118].

Solar greenhouses in Mediterranean regions offer a sustainable solution for energy savings by harnessing renewable solar energy. These greenhouses are designed to maximize sunlight capture, reducing the need for artificial lighting and heating. Solar panels and passive solar design elements can further decrease reliance on non-renewable energy sources, leading to significant cost savings and reduced carbon footprint. By integrating solar energy technologies, greenhouses in these regions can achieve high energy efficiency, maintain optimal growing conditions year-round, and contribute to environmental sustainability [57,96,119].

Within this context, heating applications in the greenhouses have an important effect on the yield as well as on the quality and the cultivation time of the products. Because of the relatively high cost and uncertain availability of fossil fuels, considerable attention has been given to new and renewable energy sources as an alternative means of heating greenhouses. As documented, the simulated energy production of photovoltaic greenhouses with a 25% photovoltaic cover ratio is sufficient (64 kWh/m^2 per year) to power greenhouse appliances for microclimate control (cooling, heating, ventilation), irrigation, and fertilization in Mediterranean countries. This is well above the average energy consumption, which ranges from 2 to 20 kWh m^{-2} per year [120]. Solar energy, in fact, is an attractive substitute for conventional fuels for the passive and active heating of greenhouses. Solar thermal energy can be stored as sensible heat, latent heat, heat of reaction, or a combination of these [58].

While heating systems are essential for extending the growing season of various vegetables in Mediterranean greenhouses during the winter, cooling systems play a crucial role in managing plant growth and development during the summer. These cooling systems help maintain optimal temperatures, preventing heat stress and ensuring consistent crop quality.

In fact, Mediterranean horticulture often relies on cooling systems to prevent thermal stress. Traditional methods like natural ventilation and cover whitening reduce radiation and photosynthetic capacity. Among the various systems available, external mobile shading and fogging stand out as effective options. Fogging, in particular, significantly reduces vapor pressure deficit (VPD), especially during early growth stages. However, it necessitates careful water management in regions with limited water resources [121]. By utilizing technologies such as evaporative cooling, shading, and ventilation, greenhouses can create a controlled environment that supports plant health and productivity throughout the hot summer months. This balanced approach allows for year-round cultivation, maximizing yields and improving the overall efficiency of greenhouse operations [64].

Regarding the various cooling systems available, a "pad and fan" system in greenhouses uses fans and porous pads to reduce interior temperatures by 3–6 °C under Mediterranean conditions and up to 10 °C with very low humidity. This system's simplicity and low water pressure requirements are notable benefits. However, its high installation and operational costs necessitate careful evaluation relative to the specific environmental conditions to ensure effective cost management [122].

A study in Greece demonstrated that fog system cooling in greenhouses, despite potentially higher operational costs, produced more homogeneous temperatures and humidities, facilitating better atmospheric mixing compared to the lower-cost natural ventilation, which resulted in high vertical temperature gradients [59,123]. In 2011, research in Spain indicated that air heating systems, although potentially costly to install and operate, could effectively control nocturnal temperatures with good performance and stability across various conditions, offering potential cost benefits through improved crop yield and quality [124].

Additionally, a study in Turkey in 2021 concluded that implementing a solar energy heating system in greenhouses could save 60–70% of the coal required for heating, thereby decreasing heating costs and overall production costs for greenhouse-grown commodities [125]. These findings emphasize the importance of considering initial installation and operational costs against potential long-term savings when selecting greenhouse climate control systems.

The control of substrate temperature relies on key factors such as the depth and span of heating elements within the soil, along with the temperature of the medium supplied into the system (for instance, employing the buried pipe system). Additionally, the fed-in water temperature and the span between heating elements are crucial considerations for the vegetation heating system. These elements collectively play a pivotal role in fine-tuning and maintaining optimal substrate temperatures, essential for effective control and management in the cultivation of crops [126]. Within this context, it was documented that the manipulation of both air and substrate temperatures has a substantial impact on the growth and development processes of protected vegetable crops. In Mediterranean greenhouses systems, it is worth noting that effective management of substrate temperature can emerge as a valuable strategy for mitigating excessive root growth in vigorous rootstock hybrids [127,128].

5. Low-Input Agronomical Strategies

5.1. Low-Input Strategies for Controlling Pest and Diseases

Greenhouse vegetable cultivation plays a pivotal role in avoiding and mitigating the effects of pests and diseases. The controlled environment within greenhouses provides a physical barrier that limits the entry of external pests, reducing the risk of infestations. Moreover, the enclosed space allows for more effective monitoring and early detection of potential threats.

For instance, among the diverse array of pests causing substantial economic losses in the Mediterranean region, nematodes represent a significant threat to greenhouse agriculture by diminishing crop yields and quality [129–131]. They necessitate costly management practices such as soil disinfection and treatment with nematicides, impacting the overall profitability and sustainability of greenhouse operations. Effective nematode control strategies are crucial to maintain productivity and mitigate financial losses in this region. Various soil disinfestation methods were evaluated over the last decades in intensive horticultural crops to reduce *Meloidogyne* nematode populations [129,132].

As previously outlined, fumigation with 1,3-dichloropropene + chloropicrin and dimethyl-disulphide achieved reductions of 87% and 78%, respectively. Non-fumigant nematicides and natural products showed efficacies ranging from 41% to 64%, while bio solarization with chicken manure reached 73%. Fumigation and bio solarization effectively lowered nematode populations below economic damage thresholds, proving profitable, especially in susceptible crops like aubergines (*S. melongena* L.) and cucumbers (*C. sativus* L.) [133].

Furthermore, solarization is an effective solution against root-knot nematodes, weeds, and soilborne pathogens. However, there is limited knowledge about its long-term effects and the impact of repeated solarization cycles. Understanding these aspects could help minimize the number of treatments required.

When properly managed, solarization offers an affordable method to significantly increase yields in regions severely affected by soilborne pathogens [134]. In addition, crop rotation in greenhouses is a crucial strategy for controlling soilborne diseases. By alternating different crops, one disrupts the life cycles of pathogens and reduces disease pressure, promoting healthier soil and improved crop yields [130].

Integrated pest management (IPM) strategies can be implemented in greenhouses, incorporating biological controls, beneficial insects, and selective pesticides to maintain a balanced ecosystem and suppress pest populations. By minimizing exposure to external environmental conditions, greenhouses create an inhospitable environment for many pests and diseases, contributing to a more resilient and sustainable approach to vegetable production. IPM programs for greenhouse crops share several common characteristics; in particular, they stand out as a crucial alternative to the conventional pest management programs [135,136].

Adoption occurs only after a comprehensive IPM strategy has been fully developed; initial implementation requires robust support from extension services, the cost of pest control under IPM should be comparable to chemical methods, and non-chemical approaches like biological control agents and resistant plant varieties must be equally accessible, dependable, and consistent in quality compared to chemical options [137]. The development of IPM programs in Mediterranean regions, particularly in southeastern Spain, where protected vegetable production is prevalent, has been driven by regulatory frameworks, subsidies, knowledge extension, and research and development. This has positioned biocontrol as the preferred pest management method. Significant factors contributing to this success include the affordability and quality of beneficial insects, advances in mass-rearing technologies, and innovative release systems like sachets, which have reduced costs [138,139]. For instance, the Almeria region in Spain, renowned for its intensive greenhouse production system, has significantly intensified the use of biological control methods. This shift has been driven by EU regulations aimed at reducing the use of pesticides and chemicals [140]. Despite its value, IPM faces challenges such as limited farmer engagement in technology development and a frequent lack of understanding of its ecological principles [141]. Indeed, globally, chemical control continues to be the primary method used in most plant health programs.

In addition to the broad spectrum of IPM strategies, biological control of arthropod pests in greenhouse crops has been successful for decades, with most commercially produced natural enemies used in this setting. However, high costs and low efficacy in some cases still hinder widespread adoption [142]. In fact, this strategy remains limited to specific sectors due to the high production and application costs of biopesticides. As thoroughly documented in prior research, the unit production cost of *Bacillus thuringiensis*-based biopesticides is competitive with chemical pesticides. New production methods, such as using starch industry wastewater (SIW) as a substrate, have enabled these formulations to reach a competitive price of $2.54/L. Profitability hinges on achieving a 5 million L annual capacity and a $15/L selling price, ensuring a payback period of under 5 years [143].

Effective pest management can be achieved through innovative, cost-reducing techniques. For example, dipping cuttings in low concentrations of mineral oil and insecticidal soap has proven highly effective against *B. tabaci* on poinsettia cuttings. Moreover, these dips are compatible with biological controls, highlighting their potential in integrated pest management strategies that combine advanced growing techniques with biopesticide applications [144].

It is important to note that biocontrol is a relatively recent plant protection strategy, with ongoing advancements in technology driving its development. Within this context, future trends in biocontrol focus on artificial diets and automation, aiming to further decrease production expenses and extend biocontrol practices to open field crops [145].

5.2. Low-Input Strategies for Optimizing Fertilizations Practices

The use of organic fertilizers or bioproducts emerges as a key strategy for fostering circular economy principles in low-input greenhouse vegetable production. By incorporating these natural inputs derived from renewable sources, a closed-loop system can be established, enhancing soil fertility, reducing dependency on synthetic chemicals, and promoting sustainable nutrient cycling. The adoption of organic and bio-based alternatives aligns seamlessly with circular economy principles, ensuring a regenerative and eco-friendly approach to greenhouse vegetable cultivation while minimizing environmental impact and supporting long-term agricultural resilience.

In the realm of the modern agricultural scenario, the ongoing conflict between Russia and Ukraine has led to increased fertilizer and energy costs globally, impacting agricultural production and supply chains. The disruption in fertilizer supplies from Ukraine, a major exporter, has resulted in a significant increase in prices, posing challenges to farmers worldwide [146–150]. The escalation of tensions between the two nations underscores the interconnectedness of geopolitical events and their ripple effects on critical sectors like agriculture.

Optimizing nitrogen fertilizer utilization in greenhouse vegetable production is crucial for environmental sustainability and global development. For instance, as was outlined in a prior study, reducing nitrogen fertilizer usage could save $1–5 million in input costs and increase avoided social costs by $1–14 million [151]. Implementing reduced fertilization practices is a cost-effective approach that maintains yields, reduces social costs and nitrogen footprint, and promotes sustainable development in greenhouse vegetable production [151].

The development of new formulations based on microorganisms, microbial *consortia*, and amino acid mixtures represents a valuable strategy to ensure sustainable organic food production [152]. As demonstrated, these products can provide a significant nitrogen content combined with a high percentage of organic matter, which is essential for limiting nitrogen leaching [153,154]. The integration of microbial consortia and amino acid mixtures into soil management practices not only enhances nutrient availability but also promotes soil health and structure, leading to more efficient and sustainable organic food production systems.

Nitrate pollution from excessive nitrogen fertigation in Mediterranean greenhouse *S. lycopersicum* L. production represents a crucial environmental issue [155,156]. Reducing fertilizer use can significantly lower costs by mitigating the increasing trend of annual total nitrogen (TN) leaching over time. Annual TN leaching losses rise linearly with increased nitrogen input, leading to higher environmental costs and regulatory penalties. By optimizing irrigation and fertilization practices, such as implementing precision fertigation, farmers can effectively manage and reduce nitrogen leaching. This approach not only cuts costs associated with excessive fertilizer use and environmental remediation but also enhances overall resource efficiency and sustainability in greenhouse vegetable production [157]. Within this context, a study in Barcelona showed that reducing nitrogen concentration from 11 mM to 7 mM decreased nitrate leaching by 70% without compromising yield or quality, and significantly lowered environmental impacts, including eutrophication, climate change, and photochemical oxidants [158].

This approach is closely related to the principles of a circular economy, where waste and by-products are repurposed to create value within the same system. Organic fertilizers, often by-products of agricultural activities, exemplify this concept by promoting sustainability throughout the agricultural supply chain.

For instance, studies have demonstrated that organic fertilizers made from pelleted poultry manure can significantly enhance soil microbial communities. These fertilizers enrich microbial populations that are crucial for maintaining and improving the soil's biochemical properties. Notably, they positively influence total nitrogen levels, overall soil pH, and soluble carbon content, which are vital for soil health and fertility [159]. The use of such organic fertilizers not only improves soil quality but also reduces reliance on synthetic fertilizers, thereby decreasing the environmental footprint of farming practices. By fostering a more sustainable and self-sufficient agricultural system, this practice supports both economic and environmental goals, ensuring long-term agricultural productivity and ecological balance [160,161].

Green manure from agroecological service crops (ASCs) and organic amendments are key for managing soil fertility, particularly by replacing synthetic fertilizers with organic ones (the input substitution approach). Over a two-year organic rotation, we compared a conventional system (SB) with two agroecological systems that incorporated ASCs along with manure (AM) and compost (AC) amendments. The results indicated that, while conventional practices yield higher production, they do not have a positive long-term impact on soil microbial communities or arthropods, unlike agroecological practices [39]. In the scenario of the development of modern fertilizer and amendments, anaerobic digestate has been identified as a suitable fertilizer with significant potential. One advantage of this product is that it is a byproduct, usable in agriculture. It is produced through microbial fermentation in an anaerobic environment, facilitated by microorganisms [162].

Recycling agricultural waste in line with organic farming practices, as highlighted by various authors, can lead to significant cost savings and substantial reductions in greenhouse gas emissions, addressing the current climate change scenario [161]. The utilization of this product in greenhouses can greatly enhance soil structure and provide substantial economic benefits, given its lower cost compared to other fertilizers [163–165].

The method of fertilizer and water application significantly impacts both environmental effects and costs. Flood irrigation, for example, leads to nitrogen overuse and inefficiency in solar greenhouse vegetable production [166,167]. In contrast, switching to fertigation reduces costs by increasing tomato yields, enhancing resource use efficiency, and decreasing annual variability. Additionally, using straw reduces nitrate leaching and gradually improves soil organic matter, further boosting cost-effectiveness and sustainability [168].

5.3. Low-Input Strategies for Optimizing Growing Technique

Implementing advanced growing techniques is essential for sustainable production in Mediterranean greenhouses, especially for cost savings. Optimized irrigation systems, precision fertigation, and integrated pest management can significantly reduce resource usage and operational costs. Additionally, factors such as soil substrates, mulching, and efficient plant growing techniques are fundamental for minimizing costs and achieving sustainable agriculture. By adopting these strategies, growers can maintain high production standards while achieving considerable financial savings and promoting environmental sustainability [30,56,169]. In fact, several factors significantly impact the costs of greenhouse production in Mediterranean regions.

The type of crop being cultivated plays a crucial role, as different crops have varying requirements for water, nutrients, and light, which can affect overall production expenses. Additionally, the target market influences costs, with high-demand crops potentially leading to increased revenue but also requiring higher investments in production and marketing. Technician availability is another critical factor; the cost and expertise of skilled labor directly affect operational efficiency and maintenance. Furthermore, operational costs, including energy for heating, cooling, and lighting, contribute substantially to the overall expense. Each of these elements interacts to shape the financial landscape of greenhouse operations, affecting both profitability and sustainability [170].

In recent years, the plant material used for greenhouse production has predominantly consisted of carefully selected, often hybrid, plants. Due to the advanced technology involved in their production, these plants are characterized by high costs, which significantly impact the overall budget of greenhouse operations. The expense of these high-quality, technologically advanced hybrids can strain financial resources, making it essential for producers to carefully consider their choice of plant material. This cost factor necessitates efficient resource management and strategic planning to ensure that the benefits of using such advanced plant material justify the investment, ultimately influencing the profitability of greenhouse farming [171–173]. As documented, transplanting unrooted cuttings into trays with rooting substrate is a key step in producing rooted cuttings. Companies can potentially lower production costs and boost profit margins by enhancing labor efficiency in this process. However, there is a notable lack of benchmarking between firms to optimize these costs [174].

As concerns the various strategies for minimizing the costs for sustainable greenhouse production, utilizing the appropriate growing substrate can offer significant advantages in vegetable cultivation within greenhouse systems. The widely adopted grafting technique enhances water and nutrient uptake in diverse growing substrates, enabling the cultivation of vegetables even in challenging media [175]. The choice of an appropriate substrate, in fact, plays a crucial role in influencing both the yield and quality of vegetable crops. Notably, a trial conducted on greenhouse cucumber cultivation revealed that wood fiber resulted in the highest crop yields, whereas perlite led to slightly lower yields [176]. Moreover, variations in nutritional content were evident, with cucumber fruits from summer cultivation displaying higher levels of dry matter, vitamin C, total sugars, calcium, and phosphorus. Conversely, fruits from autumn cultivation exhibited increased levels of nitrogen and potassium. These findings underscore the significance of substrate selection in optimizing both yield and nutritional composition in vegetable production [176,177].

In another case study, a cucumber greenhouse trial with diverse substrates (peat + carbonized rice hull, peat + wood chips, peat + bark, and perlite 100%) revealed significant impacts on cucumber quality components. Negative correlations, particularly between calcium and magnesium, were noted in plant element analysis. Positive correlations were observed between root and cucumber fruit nutrient uptake, emphasizing the complex relationships influenced by substrate composition [178]. As documented, reusing soil substrate in soilless greenhouse cultivation significantly reduces waste and operational costs while enhancing sustainability. This practice minimizes substrate disposal expenses and supports continuous soil health management [179].

A promising approach to reducing greenhouse harvesting labor costs is through the robotization and automation of key cultural practices, particularly harvesting. The integration of robotic systems into greenhouses offers a significant advancement by automating labor-intensive tasks such as pruning, weeding, and harvesting. Robotic harvesters, equipped with advanced sensors and precision tools, efficiently perform picking, sorting, and packaging with high accuracy and speed [180–182]. This not only cuts down on manual labor costs but also enhances overall operational efficiency and productivity. By adopting greenhouse robotization, growers can achieve substantial cost savings and improved profitability, making it a valuable investment for modern agricultural practices. In the context of the Mediterranean region, the GREENBOT Dataset has recently been developed, which is a multimodal mobile robotic dataset for a typical Mediterranean greenhouse [183]. The dataset, collected via a mobile platform equipped with sensors in a Mediterranean tomato greenhouse, enables the creation of detailed 3D plant models. These data offer the potential for applications like robotized spraying in controlled environments.

6. Conclusions

This review highlights the significance of the Mediterranean greenhouse farming model, emphasizing its reliance on low-input strategies to optimize both yield and quality. In today's agricultural landscape, Mediterranean protected horticulture is crucial for year-round production of high-value crops. Key strategies such as refined irrigation, energy-efficient climate control, and integrated pest management are vital for enhancing cost efficiency while ensuring robust yields and superior product quality. Looking ahead, the adoption of advanced technologies—like predictive models, automation, robotics, and sensor-based systems—holds promise for further reducing resource inputs and enhancing sustainability. This review aims to inspire researchers globally to consider these alternative agricultural strategies, demonstrating that such innovations can offer significant benefits to growers beyond the Mediterranean region.

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