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Greenhouse Tomato Technologies and Their Influence in Mediterranean Region

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Abstract

Tomato (*Solanum lycopersicum* L.) is the most consumed vegetable and one of the most studied crops in the world. Over the years, several technologies have been studied and applied to crop production towards higher productivity, quality, and production efficiency. This chapter reviews greenhouse tomato production, cropping systems, and environmental conditioning, focusing on technological developments and the latest reclaimed water trends that have started to take off in the context of increasing water scarcity due to climate change. Following worldwide research trends and policies, the influence of the different technologies in fresh tomato production and the use of reclaimed water or reuse of treated nutrient solution is explored as it is expected to be a great advance in the Mediterranean region in the next years, and it is of the utmost importance, as the region increasingly suffers from climate change effects.

Keywords: horticultural practices, hydroponics, nutrient recovery, reclaimed water, *Solanum lycopersicum* L

1. Introduction

The United Nations (UN) Sustainable Development Goals aim to ensure sustainable food production systems and the implementation of resilient agricultural practices that increase productivity and production by 2030. At the same time, it is required to achieve sustainable consumption and production patterns [1].

Tomato (*Solanum lycopersicum* L.) is one of the most consumed vegetables in the world due to its nutritional characteristics and benefits to health [2, 3]. In 2021, world tomato production was around 189,133 million tonnes, with China as the country with the highest world production, followed by India and the Mediterranean basin, respectively [4]. In the report “The 2017 Agricultural Outlook Conference,” EU forecasts indicated that fresh tomato production would remain stable despite the expected increase in productivity caused by wider production seasons [5]. Rising temperatures and extreme weather conditions, changing rainfall and snow cover patterns, as well as the increase in the frequency of floods and droughts due to climate change, are a challenge for the agricultural sector [6]. These factors, allied with the growth in world’s population and the need for food availability, are the driving force behind the

sector's progress. Exportation, consumer demand for quality and availability, competitively with other markets and climatic challenges influence tomato production around the world and technological solutions, help producers to face these demands [6]. Greenhouses for tomato production can be a means to increase productivity with efficient use of water, nutrients, and energy. In order to achieve optimal production conditions for both daytime and night-time temperatures, there is a significantly high energy consumption which can be overcome by adopting new climate control approaches to substitute the use of conventional energy, with cogeneration or renewable energy sources [7]. Nowadays, there are generically two types of greenhouses, in different geographic regions, with different degrees of sophistication and applied technologies, depending on climatic and socio-economics conditions: Mediterranean basin countries use typically low-tech, plastic-covered greenhouses; Northern Europe and the United States use glass greenhouses with more technologic solutions [8]. Each degree in complexity induces a new degree of microclimatic modification and adds new layers of benefits: high-tech greenhouses are expensive and involve high initial investment but lead to higher yields [7]. On the other hand, low-tech, plastic greenhouses, with mostly natural ventilation, are a low-cost solution that enables higher productions and wider production seasons than an open-field, with low initial investment [7]. However, the depletion of solar UV in greenhouse crops might compromise the sensorial perception of the fruits compared to open-field ones [3, 9]. Some events can boost the evolution of greenhouses, as is the case of west Portugal, increasing innovation as the greenhouses have been substituted and the brands expand their activity [10]. In this case, the boost of technological advances arrived with a natural disaster in 2009 that shredded several structures and forced the producers to rebuild, with State support, in an opportunity to rethink, improve and adopt more sustainable structures to achieve the best yields with the lowest environmental impacts [11].

In recent years, new technologies for greenhouse production have been developed to improve efficiency in water, energy, and chemical use, as well as fruit quality and shelf life [12]. Nevertheless, experience shows that the transfer of technologies and practices from North Europe, as they are more sophisticated and high-tech, to realities with different climatic conditions and socio-economic environments does not bring good results. Technology transfer should be adapted, tested, and validated to local requirements [8]. Therefore, crop management, technics and technologies have been tested. Some of them had success and were implemented, but others were left behind [8].

2. Varieties, grafting and rootstocks

New cultivars are commercialized every year, mostly hybrids, and their choosing, along with fruit number per cluster, affects fruit weight and disease resistance [13].

The European's Court of Justice decision of July 2018 is being contested by hundreds of European researchers asking EU institutions to revert the decision of including genome-edited organisms, with no foreign DNA, in the restricted legislation for Genetic Modified Organisms (GMO), but instead fall under the conventionally bred varieties regime under penalty that, if not, Europe's science and agriculture fall behind the rest of the world in such crucial tool for production in the face of climate change [14, 15].

Grafting is widely used as a rapid tool to increase environmental stress tolerance on crops, and currently, most crops are grown as scion-rootstock arrangements

[16]. Although this technique requires more labour for breeders, it promotes resistance to biotic and abiotic stresses, promotes more vigorous plants or higher yield, and improves fruit quality [7, 16, 17]. Since rootstocks can affect nutrient uptake, selecting rootstocks with higher nitrogen acquisition ability lead to a decrease in N fertilizer application without affecting tomato yields, while minimizing environmental pollution [18]. The use of highly resistant transgenic plants as rootstocks and grafted onto non-transgenic tomato scion result in non-transgenic plants that may evade the concern of GMO biosafety regulation, while successfully transferring resistance to the scions [17]. On the contrary, some reports state that in the absence of any induced stress, rootstocks have no effects on crop growth and water relations [19] and, under optimal conditions, some rootstocks may even reduce the growth of the grafted plant [16].

Despite the several studies available, tomato growers are not persuaded to prune clusters to a determined number or use reports as a base because of the conflicting results they present [20]. Instead, they go by the requirements of the market, the length of the cycle and their own experience [6], preferring to test on a small scale on their own before applying any of the suggested techniques. In a region most affected by climate change, all the biotechnology must be used to fight its effects.

3. Production systems

Tomato can be planted on substrates or on soil; in this last case, most producers use mulching plastic films [21]. Greenhouse provide ideal environmental conditions for the development of diseases; in addition, soil production brings some challenges as salinization and soil diseases resulting from the lack of crop rotation [22]. Chemical soil disinfection is the primary method used to manage soil-borne plant pathogens, reduce nematode populations, control soil sickness and allow profitable production [23, 24]. Soil solarization was introduced in the 1970s and is used worldwide as an environmentally friendly alternative to chemical disinfestation, with proven results in inducing physical, chemical and microbiological modifications in the soil, stimulating root growth and crop yield [25], having the advantage of non-toxicity, that is one of the greatest concerns related to other treatments.

Another string of action against the use of chemical pesticides is the implementation of different pest management strategies such as the use of intercrop plants with natural pesticides properties [23]. Improving soil quality is another challenge in this cultivation system, since it is critical for fertility and crop health [26]. The addition of compost for increasing soil organic matter and providing nutrients for the crop or the addition of biochar as soil amendment can increase soil sustainability and crop productivity by the increase on carbon sequester and nitrogen retention [26]. Combining soil solarization with organic fertilization techniques was proven to maximize their effects, achieving higher soil temperatures and release of volatile compounds, resulting in higher mineral availability and improved yields [27, 28].

Over the years, greenhouse soil production has been gradually substituted by hydroponic soilless production, with Nutrient Film Technique (NFT) systems or, more usual, on sacks of substrate (rockwool, coconut fiber, perlite or vermiculite) [29, 30] that provide a much uniform medium and allow more control of production conditions. Several substrates were studied over the years, but only the most stable ones remained. In Europe, greenhouse tomatoes are mostly produced in substrate systems, mainly rockwool [30], with individual drippers to plant-by-plant

irrigation [29]. All plant nutrients are supplied constantly in the irrigation water, and the fertilizer mixing, pH and electrical conductivity (EC) are continually monitored and can be electronically controlled. By being soilless, hydroponic systems protect crops from phytosanitary problems by starting out clean [29]. Rockwool is made from rock fiber that can be steam-sterilized and reused and provides roots with the ideal environment to grow [31]. The slabs can be used for a second, and sometimes a third, crop. Prior to reuse, the slabs are sterilized, and new plastic sleeves are placed around the slabs [13]. Growing environmental concerns about the amount of rockwool waste generated led to some attempts to find suitable substrate substitutes: organic or inorganic substrate, with one component or mixtures (sheep wool, cultivated *Sphagnum* biomass, hemp sawdust, coco coir, volcanic sand, perlite) [20, 32].

NFT system, on the other hand, consists of growing plants without the use of a substrate, but instead, conserving a shallow nutrient solution (NS) around the roots and can improve yield up to three times, depending on NS concentration [33]. In [34] the cultivation of tomatoes in soil was compared with NFT production (closed cycle) and rockwool (open cycle). The results show that hydroponic systems enhanced earliness in at least 8 days and yield in at least 10 t/ha compared to soil. Higher yield, less water and fertilizer application were achieved in NFT, thus reducing the environmental impact.

4. Microorganisms/inoculation

The introduction of specific microorganisms into the crop system result in several benefits such as improving nutrient use efficiency, plant growth, fruit weight and disease control [35, 36]. Studies in plant inoculation with bacteria and fungi demonstrate the positive effects of *Pseudomonas putida*, *Trichoderma atroviride* or *Methylobacterium* in promoting the reproductive growth of tomatoes under hydroponic growing systems, improving yields by >15% in organic medium [35, 37, 38]. Bacteria of genus *Methylobacterium* have been found to significantly reduce disease symptoms and lower the disease index value of *Ralstonia solanacearum* in inoculated plants when compared to non-inoculated ones, suggesting its potential use as a biocontrol agent in tomatoes [38]. Substantial post-harvest disease control can also be accomplished by inoculation (*Bacillus subtilis* strain QST 713) when combined with storage at 13°C [36].

5. Pollinators

Bumblebees (*Bombus* spp.) are commonly used for pollination in greenhouse, being the principal pollinator in tomatoes [39]. Its use is very effective and economically profitable, inducing greater fruit sets, more regular form, more top-grade fruits, and lowest defects [40, 41]. Besides pollination, [42] conducted a study to assess the contribution of bumblebees for the dissemination of two fungi, in greenhouse tomato and sweet pepper, for control of pests and plant disease. The authors demonstrate that pollinators can influence pests and disease control since the simultaneous spread of *Beauveria bassiana* and *Clonostachys rosea* inoculums by bumblebees contributed to controlling greenhouse whitefly, reducing plant pests, and gray mold (*Botrytis cinerea*), having no effect on bee mortality.

Using commercial bumblebees raises some ecological concerns and real problems that have not been addressed: as colonies are transported all over the world, subspecies are introduced into non-endemic regions, there is competition between species, genetic pollution of native species, parasites and pathogens transmission and changes in the native flora [41]. Nevertheless, bumblebees used for pollination are a better choice compared to plant growth regulators that could also present environmental hazards and furthermore, growers have more careful in using chemicals in the greenhouse when using bumblebees [43]. To minimize the problems, hive boxes should be disposed of safely. The development of commercial native bumblebees must be investigated, and legislation should address and regulate its use [43].

6. Greenhouse environment

Greenhouse environment can be altered by several factors as the choice of cover materials, lightening, heating or cooling, aeration, CO₂ application, the use of evaporative systems and others.

6.1 Greenhouse materials

Covering materials increase fruit yield and quality by influencing the environment inside, such as thermal conditions [44, 45]. Solar radiation is the main factor affecting plant photosynthesis and, consequently, plant growth [46]. Ultraviolet radiation (UV) depletion affects the sensorial and nutritional quality of tomatoes, and off-season fruits are less tasteful than in-season fruit, and these are usually less tasteful than open-field ones [9]. As a result, greenhouse cladding materials characteristics are very important, as they affect transmitted radiation, reflectivity, and absorptivity [45–48], leading to different interior environmental conditions (with consequences on air temperature, relative humidity, and vapor pressure deficit (VPD)) [49], affecting physiological processes and yield, remaining a primary concern in greenhouse production [48, 49]. An appropriate covering material is assumed to combine low transmittance in the long wave band with the maximum transmittance in the photosynthetically active radiation (PAR) spectrum [50].

Greenhouses provide a better environment for plants to grow in cold climates by conserving heat, but in hotter climates, like the Mediterranean, cooling systems need to be used to lower temperature and increase humidity to provide an adequate environment [51]. The inefficiency of greenhouse covers, such as low visible light transmittance and low near-infrared reflectance [52], led to the need for heating or cooling greenhouses, which are very energy-consuming processes. To reduce energy consumption, in the last decades, the use of thermal-resistant materials, curtains, alternative sources of energy and techniques to reduce energy loss gained huge importance [45].

The thickness of the cladding material, dirtiness, the use of additives for the radiation spectrum and the condensation on the interior affect radiation transmittance through the covering material [44, 47, 53]. Plastic materials are the most popular cover mainly by the use of low-density polyethylene (LDPE), the copolymer of ethylene and vinyl acetate (EVA) and polyvinylchloride (PVC) [45, 48, 54]. Polyethylene films are mostly LDPE due to their relatively good mechanical and optical properties (flexible, transparent to thermal radiation and with 70–95% solar transmittance)

combined with a competitive market price [48]. Polycarbonate covers are more affordable than glass and have good thermal efficiency but avoid the transmittance of UV light, allowing only 400 nm or higher wavelengths to reach the fruits [55]. UV-A/B radiation, control several plant functions, and a tomato grown under reduced UV radiation has its quality compromised [3]. By choosing covering materials with higher UV-transmittance in tomato production, the anti-oxidative capacity of fruits can be improved without influencing fruit weight [56].

Tantau et al. [47] tested 20 different covering materials and measured PAR and solar radiation, and compared them to the outside conditions. The results corroborate the early ones and stated that condensation on the internal surfaces of the cladding materials reduces PAR transmittance. During the 5 years, the ageing effect on the material's light transmission was not detected. Covers, structures, and fixed objects hanging over the plants can block radiation in 25 to 50% [50].

Shade nets can protect greenhouse crops from high light intensities, and its use is a simple and very effective, strategy for cooling greenhouses during the summer [50, 57]. In Greece, [58] tested the effects on microclimate, crop production and quality of tomato grown under four different shade nets, finding that shading does not reduce dry matter content and, on the other hand, increase leaf area index, the number of fruits per plant, and the total fresh tomato yield. Tomato cracking was reduced by 50% in shading, and marketable tomato fruit yield increased by around 50% compared to non-shaded treatments.

In [44], tomato color development and lycopene accumulation were assessed in fruits grown in a) double-layer polyethylene with infrared transmission and anti-condensate (IR/AC) additives and b) flat glass 4 mm thick coated with a 15% CaCO_3 solution greenhouses. Their results suggest that the lycopene biosynthesis process is affected by the season of production, temperature, and lighting conditions and in the 32nd week, lycopene content was higher in the fruits collected in a double layer of polyethylene greenhouses. The application of 15% CaCO_3 solution helped to control the temperature but had negative effects on lycopene biosynthesis. Flat glass with a CaCO_3 coating showed higher light transmission and, between 380 and 600 nm wavelength, the glass coating allowed higher light transmission than the double layer of polyethylene, but at 650–760 nm, plastic cover presented higher light transmission. Pigmented coatings are found to reflect incident solar radiation in the infrared wavelengths (NIR), while maintaining visible light (VIS) to be transmitted and reducing heat. It is possible to have higher transmittance in VIS than NIR using synthetic diamond particles with the low optimum volume fraction, 0.89%, in powder form and with nearly 1.19 μm as optimum diameter, and so it could be used as a pigment material for reducing cooling energy requirements in hot climates [51]. Colored paints are used for cooling as well. [59] studied coated flakes of metal to achieve enhanced solar reflectance and lower inside temperatures. They found that flakes of metal coated with a single layer of iron oxide or a double layer of iron oxide on silica (<200 nm thickness) have lower solar absorbance than conventional paints.

Public health concerns regarding chemical pesticide toxicity restrict their use, but they are still very important in agriculture, so another innovative approach to cover materials was made [60], where nanocomposite film was used as a pesticide delivery system. The authors loaded deltamethrin into halloysite nanotubes, which resulted in improvements in the flexible modulus of linear LDPE films and obtained continuous release for 60 days. The results revealed efficacy in repelling mature aphids and eradication of young aphids and thrips when placed at 1 m of plant's boundary.

6.2 Lighting

As light is a major factor in plant growth and its insufficiency is a key abiotic stress, limiting plant development and yield [61], several studies try to get insight into the influence of additional light sources, the extension of photoperiods, spectrum ranges and/or complementary light effect on plant development [50, 61–65]. The extension of photoperiods has been studied for more than three decades to improve leaf fresh weight and tomato yields and to support year-round production in greenhouse horticulture where natural light is limited [65, 66]. In the early studies, the common source of supplementary light were high-intensity discharge light sources such as metal halide lamps and high-pressure sodium (HPS) lamps, but nowadays, light-emitting diodes (LED) are the most common technology used [65]. High-intensity discharge light systems are very inefficient and produce high amounts of radiant heat [65]; LEDs, on the other hand, are an energy-efficient alternative since it converts electricity to light much more efficiently [65, 67] and can be designed to fit the spectral demand of the plants [61, 65].

All wavelengths proved to affect crops positively, but different light spectrum wavelengths induce specific effects on plants [68]. Blue light (450–495 nm) is reported as a chlorophyll formation regulator and growth promotor [69, 70]. There is a generalized perception that green light does not contribute or is less effective in growth than other ranges of the visible spectrum [71], but contradictory results can be found in the literature on its benefits and disadvantages. Several studies in lettuce claim that enriching a white or red/blue spectrum with green light (while keeping light intensity identical) can increase plant growth and yield [72]. At the same time, others reported that green light (510–585 nm) penetrates the canopy more than red or blue ranges [71], improving the vertical light profile and the irradiance in otherwise shaded leaves. So, it can be hypothesized that green light may have some importance in plant growth [73].

Red light (600–740 nm) is important for the development of the photosynthetic system and is often associated with the morphological adjustment of plants to the environment [69]. It is reported that red lighting environments impose physiologic responses and affect floral initiation, chlorophyll, and carotenoid contents [68]. A prolonged period of monochromatic red-light treatment has shown positive effects on the yield and quality of greenhouse tomatoes [68, 70].

According to [69], plants respond to UV-A treatments through cryptochromes and phototropins and under UV-A/B irradiation treatments, plants presented enhanced flowering, fruit ripening synchronization and fruit's nutritional properties as fruit °Brix and other physicochemical characteristics [3]. Combinations of a specific wavelength from LEDs appears to enhance nutritional and health characteristics of horticultural crops [56, 66]. In fact, the effects of supplemental lighting with three different lighting source approaches on the dynamics of fruit growth and composition in soluble sugars, starch and acids in tomatoes were studied by [65] and reinforced the results of [63] with the discovery that regarding the application of a low supplementary dose of far-red LED light to red/blue light, fruit quality is improved: glucose, fructose and sucrose were significantly increased in pericarp, having a great impact in taste characteristics of tomato [74]. When applying intracanopy red + far-red LED light, fruit yield can be 50% higher compared to the use of HPS lamps while improving fruit quality and of-season tomato flavor, reducing energy use by 70% [75].

In [64], light-induced change in tomato metabolic processes morphology and production response to exposure to three durations of far-red (FR) supplemental

lighting is investigated, combined with red and blue lightning. The results show that supplemental FR light resulted in longer plants, with a higher leaf length/width ratio and larger leaf area compared with the control, which led to a more homogeneous intracanopy light distribution. Contradicting the results of [65], in [64] reported a certain decrease in soluble sugar content of the ripe tomato fruit even though a 7–12% ripe fruit increment was achieved. With no significant differences, 0.5 h treatment was the most favorable, since it stimulates growth and production, as the others, but is less energy consuming.

The application of supplemental light within the lower canopy or inter canopy could be a better way to suppress light insufficiency than traditional supplemental light [61]. LEDs permit placement closer to crop canopies due to the cool surfaces, which greatly reduces electrical energy requirements. Light distribution can be enhanced while decreasing the waste of light that other technologies present and spectral blends can be tailored for each purpose [66]. LED interlighting in tomatoes resulted in increases irradiation levels [61] and yield by 24–36% [76]. Li et al. [77] related the application of interlighting with higher water use efficiency in tomatoes. Supplemental lighting provided from underneath the canopy (UC) or within the inner canopy (IC) in single-truss tomato plants significantly promoted leaf photosynthetic activities, plant growth, and fruit production in plants exposed to low solar irradiation levels [61]. The use of UC had a greater contribution to fruit yield; however, IC induced an increase of soluble solid contents in fruit due to the higher exposure of the fruit to direct supplemental light. Moreover, the cost–benefit analysis shows that the application of UC may be more economically attractive than the use of IC. The application of narrow-band red and blue light as intracanopy lightning did not have any negative effects on fruit quality, and, with solely white LED interlighting, positive effects were demonstrated for tomatoes [78]. LED lighting may also be a suitable way to control pest insects and prevent physiological diseases stimulated by low-intensity or narrow-spectrum [66].

The influence of low irradiance light pulses (LP) of 15 min each was tested during the night, with a frequency of 2 h and 4 h, applied to plants in a greenhouse with controlled temperature after fruiting until ripening in red [79]. Results demonstrated that low irradiance LP treatment reduces the concentration of free sugars, amino acids, and other metabolites without impact on other fruit quality parameters such as firmness. Plants exposed to 15 min LP every 2 h during the night presented an increased yield of 18%.

6.3 Energy requirements

Intensive greenhouse energy requirements lead to important energy costs that could easily constitute 15 to 30% of a greenhouse operation's annual costs [80] and, in some cases, could even reach 50% of the total annual cost [81]. Nowadays, with growing climate change concerns, and actual challenges, limitations in fossil energy supply and heating costs rising for conventional coal, oil and natural gas, the use of energy conservation techniques and innovative applications of renewable energy have gained increased importance to heat or cool the greenhouses, while improving energy utilization, contributing directly to the reduction of greenhouse gas (GHG) emissions and aiding to reduce production costs [82, 83]. Thus, greenhouse systems based on solar energy to increase air temperature or for energy production seem very appealing and have been studied along the Mediterranean basin. Among them, it could be found: rock-bed storage, water storage, movable insulation, ground air collectors,

phase change material storage, north wall storage and the installation of photovoltaic panels [83]. These systems are capable, to more or less extent, of increasing the greenhouse air temperature during the night compared to the conventional greenhouse and increasing yields [84, 85] and the application of a passive solar system like polyethylene sleeves along rows can lead to 8% energy saving in heated greenhouses [86] while the use of north wall insulation systems can achieve 31.7% reduction in heating requirements [87].

Using semi-transparent build-in integrated photovoltaics mounted on 20% of the greenhouse roof area, [88] found no significant differences in tomato development compared to control even though a 35 to 40% reduction of solar radiation was observed, resulting in 1 to 3°C decrease in air temperature on clear days, not affecting relative humidity.

Other renewable energy sources as small/medium-sized wind turbines and biomass, could also be explored to reduce energy costs in heated greenhouses [89]. Tomato crop is negatively affected by low temperatures; however, a balance between energy use and crop production can be achieved. Reducing heating set points during the night could represent a huge energy-saving measure without affecting total yield, but loss of early production profit due to the delay of harvest has to be weighted by producers [90].

6.4 Environmental control

High humidity in a greenhouse is favorable to fungal disease development, so its control is of extreme importance. Ventilation has a very important contribution in reducing high relative humidity, minimizing diseases and, consequently, minimizing the use of chemicals in greenhouses [91]. Natural ventilation depends on the wind and temperature differences between outside and inside, rely on doors, openings on the roof and/or in the side walls [91], and uses no energy but is usually insufficient. Forced ventilation for cooling and air humidity regulation purposes, and mostly the fan-pad system, is widely used worldwide to control high temperatures in summer, provide uniform airflow, and control CO₂ concentrations levels [92]; however, it also comes with an energy cost. To reduce the costs, natural ventilation combined with mechanical cooling could be used [93], but also, the maintenance of equipment is of great importance [94].

Aeration practices are proven to increase tomato yield and fruit quality but also to intensify soil CO₂ and N₂O emissions without, however, significantly increasing the overall greenhouse [95–98]. Some studies indicate the existence of complex interactions among growing seasons, irrigation method, and N application, which indicate that in increasing global warming scenario, using aerated irrigation in combination with reducing nitrogen fertilizer rate could be an effective way of maintaining crop yield while reducing soil net GHG emissions [98].

Low carbon dioxide is one of the primary factors affecting the quality of greenhouse tomatoes [99]. In general, the net photosynthetic rate increases with increasing CO₂ concentration, 800–1000 $\mu\text{L L}^{-1}$ considered the optimal CO₂ concentration for plant development [100]. Thus, CO₂ enrichment in controlled environmental conditions is known to effectively promote photosynthesis, enhance growth and production, increase water use efficiency (WUE) and is widely used around the world [101]. The contents of lycopene, β -carotene, ascorbic acid, sugars, titrable acidity and sugar/acid ratio were increased in fruits grown in CO₂ enrichment environment, and organoleptic characteristics were benefited [99].

For energy and environmental sustainability, alternatives to traditional CO₂ enrichment devices are being studied, and [101] suggested the symbiosis between industrial installations (production of CO₂) and greenhouses to reduce the overall amounts of CO₂ released in the atmosphere, recommending, however, that a case-by-case analysis be conducted to assess the environmental benefit and economic feasibility.

To achieve desired growing conditions in summer, the control of air temperature and VPD by fogging technology is intensifying. This technology has been reported as useful in reducing the need for natural ventilation, allowing for higher CO₂ concentrations to be maintained inside greenhouses and can influence the number and mass of the fruits [102, 103]. Evaporative fogging systems are considered better than pad-fan systems for achieving cooling and increasing absolute humidity in a more uniform spatial distribution, providing higher water evaporation while keeping the plants dry [104], although its efficiency depends on system design parameters and conditions. However, operation costs and water availability must be assessed prior to the installation of such systems [103].

Each environmental control technology and crop management strategies have huge impacts in greenhouse production. The interactions between those two vectors (**Table 1**) enhance the beneficial effects, resulting in more thoughtful greenhouses, more efficient, productive, and capable of contributing to sustainable production in the face of climatic change and world challenges for feeding the increasing population.

Greenhouse environmental control systems are becoming more sophisticated, using more and more sensors to improve control, and as sensor prices are reduced due to development and higher offer, they are being used more frequently [105]. These systems can collect outside and inside data about temperatures, wind direction, sunlight, carbon dioxide levels, and humidity, among other parameters, to better control the greenhouse environment for optimizing cultivating conditions: opening and closing windows, adjusting NS, start/stop forced ventilation or heating to obtain the desired temperature, humidity, light, pH, EC, water, and nutrition levels [105, 106].

Automation programmes, timers, temperature, humidity, pH, CE and other sensor are widely used to control fertigation [107, 108]. Other than that, recent developments in automation and robotics aim to increase production efficiency in greenhouses by studding solutions for labour-demanding tasks [7]. Most of the studies present solutions for harvesting robots with successful results [109–111]. The fruit's physical and mechanical properties were studied by [112] to allow automated harvest and other studies are reported in tomato identification by the artificial vision-robotic system [113]. A pesticide robot spray application was tested in tomatoes that provided encouraging results with the same or improved performance in comparison to traditional pesticide application methods [114]. Besides mechanical harvesting, a Greenhouse Robotic Worker - GRoW - can perform various tasks, like, trimming, monitoring the crop and pollinating, estimating a reduction of labour costs up to 50% [110].

7. Irrigation techniques and reclaimed water trends

Drip fertigation is one of the best techniques for applying water and fertilizer to fruit and vegetables and has been widely used in greenhouses [115, 116] associated with automation programmes based on timers, sensors and models or manual

		Irradiation	RH	VPD	Temp.	CO ₂	Air Flow	Heating Req.	Emissions	Yield	Quality	Shelf Life	Diseases
Covers	Plastic	+						—					
	Glass	+						+		+	+		
	Additives	+			+						+		
	Nets	—			+					+	+		
	CaCO ₃	—	+		+						—		
Complemental light	Extent Photoperiod									+	+		
	Far-Red										+		
	Red									+	+		
	Blue									+			
	Green									^			
	UV-A/UV-B									+	+	+	
	Interlighting									+	+		
	Under Canopy									+			
	Pulses									+			
Energy	Heating				+					+			—
	Cooling				+					+			+
	Ventilation		+		+	+	+						+
Other environment	Evaporative Systems			+	+	+				+			
	CO ₂									+	+		
	Aeration								—	+	+		

		Irradiation	RH	VPD	Temp.	CO ₂	Air Flow	Heating Req.	Emissions	Yield	Quality	Shelf Life	Diseases
Variety/ Grafting/ / Rootstock	Adequate Cultivar									+	+	+	+
	Grafting & rootstock									^	^		+
Medium	Soil									—			—
	Substrate									+			+
	NFT									+			+
Others	Microorganism inoculation									+		+	+
	Pollinators									+	+		+

Table 1.
Summary of influence for greenhouses. (+) positive effect; (–) negative effect; (^) conflicting results.

activation [107, 108]. Negative pressure irrigation is also a commonly used irrigation technic in greenhouses [117]. It supplies water at a negative pressure, controlling soil water content, allowing automatic irrigation according to crop requirements [118], can increase yield, fruit height, stem diameter, and significantly improve water use efficiency (WUE) when compared to drip irrigation [116]. Partial root-zone irrigation technique has also been studied to reduce water consumption with low yield loss. Alternate partial root-zone irrigation, in which half of the root system is irrigated normally, while the other half is exposed to drying soil, improves WUE, enhances root activity and can increase yield, when compared to conventional drip irrigation [119]. Bench sub-irrigation system reduces plant height, leaf area, total fresh and dry weight but as NS management is very simple with this technique, it could be used for closed cycle cultivation even in low-tech greenhouses [120] (Montesano et al., 2010). Water pillow irrigation is a new method with quite high irrigation water efficiency studied by [115]. The results in greenhouse tomato showed that irrigation water using water pillow was 52% less than in drip irrigation, the total yield and yield per plant were 17% higher, and no weed development was observed in water pillow in contrast with drip irrigation, and fruits had better physic-chemical characteristics (pH, titration acidity, °brix, total dry matter, and color values).

In soilless culture, the NS can be single-used in an open, non-circulating system or reused in closed, recirculating systems [107]. Non-circulating systems use NS supplied in each irrigation and account for runoff losses [107] while recirculating systems collect leftover NS, blend it with fresh NS, and recirculate it in subsequent irrigations [29, 120], increasing water and nutrient use efficiency, despite some yield reduction that can occur, induced by salinization in root zone [2, 107, 121]. One of the main problems associated with these systems is the potential spread of plant root pathogens and the accumulation of other chemical compounds [122]. Most growers use physical and chemical disinfection methods to treat the drain water and reduce the risk of spreading root diseases. Pasteurization, ultraviolet treatment or chlorine dosing are the most common treatments [29] but heat, sonication, application of copper and silver ions, active carbon absorption, hydrogen peroxide, as well as dissolution of ozone into bulk irrigation solutions are used as well. Ozone effectively reduces chemical contaminant and pathogen levels in greenhouse irrigation water [123].

High NS electrical conductivity enhances sensorial quality of greenhouse tomatoes as studies reveal that under this condition, fruits are more flavourful, redder, smaller, softer at touch, firmer in the mouth, crunchier and sourer, being usually preferred by consumers in sensorial tests [121]. The sensory quality is accompanied by higher sugar and acid content and aroma volatiles [124, 125]. Elevating the EC of the NS can thus be a simple way to improve tomato fruit quality [124].

In the Mediterranean, deficit irrigation and intensive cultivation are common practices which leads to salinization, poor irrigation, and poor soil quality. In a simulated Mediterranean greenhouse, under high salinity irrigation $EC_w = 3.5 \text{ dS m}^{-1}$, [126] concluded that early harvest and early termination of the season have no significant impact on tomato yield while alleviating the pressure over natural resources.

Inducing deficit irrigation can promote quality to some extent [127, 128], but scheduling could greatly affect the results [128]. Regulated deficit irrigation (RDI) is meant to ensure an optimal crop water status in most sensitive to water-stress phenological phases and restrict irrigation in the other development phases [129]. Several studies have been made, and the results clearly point out that WUE increase although the yield is reduced tomato [130]. In northwest China, [131] determined that the application of 1/3 or 2/3 of the normally full irrigation amount at flowering

and fruit development stages, and no water stress in the other growth stages, can result in a good concession between yield and quality of tomato. On the contrary, [128] showed that, at the seedling stage, the application of 1/3 and 2/3 of full irrigation did not significantly impact water consumption, total yield and fruit quality, but the application of 1/3 of full irrigation at flowering and fruit development stage had a negative effect in total yield. The application of 1/3 or 2/3 of full irrigation at the fruit maturation stage also impacts negatively in total yield. However, despite the negative results in yield, fruit quality was significantly increased, concluding that tomato yield is sensitive to water deficit during the fruit development stage and fruit maturation stage, while fruit quality is mainly affected by water stress during the fruit maturation stage. The application of 2/3 full irrigation at fruit development stage had no significant effects on yield and quality. Some authors defend that RDI based on leaf water potential has the potential to improve the accuracy of irrigation scheduling, since it integrates the soil-water-plant relations, which could lead to important reductions on yield loss [130].

Last trends in greenhouse water use (and in agriculture in general), point to reclaimed water utilization of various sources, boosted by recent legislative changes in the UE, and, namely, in the south, by increasing water scarcity. It is expected that in the following years, the use of these water sources also sees an intensification to fight climate change consequences, although there are some challenges and concerns that need to be addressed to its widespread use. Israel is pioneer in reclaimed water use in agriculture, since water scarcity in the country is a hard reality, but even there, concerns are considered, and precautions are being taken to minimize and overcome health security risks [132].

Most studies approach the use of treated urban wastewater, but other alternatives are also considered as reuse rainfall, drainage from greenhouses and aquaponic water, with positive results in yield and quality but fewer details about pathogenic or compound accumulation in fruit [30, 133–135] which consists of vital information for assessing the viability of the use of these resources. As an example, in Portugal, the reuse of NS in greenhouses has been used for some producers and for some time now, but there was no evidence in literature about this practice in the country until 2018 with the announcement of TomatInov Project and the consecutive divulgation and demonstration actions [136] where the NS is reused in a semi-closed system and the demonstration, in 2020, of full closed system by New Growing Systems [137], which reveals that although many technologies are in use, there is a lot of room for improvement.

8. Conclusion and directions

The increasing challenges related to anticipated global climate change, increasing world population and demand for healthier products push the research and the application of more efficient production techniques. Reducing greenhouse energy consumption by increasing energy efficiency and by the application of renewable energy sources is imperative. Face water shortages by changing irrigation methods and pursuing water use efficiency as well as the use of reclaimed water, control environmental conditions, use tailored light only where necessary and sustainable substrate materials, breed cultivars that are more resistant to biotic and abiotic stresses, and the use of rootstock to induce resistance or vigor but generate non-GMO products

alleviating biosafety concerns, are all pieces of an integrated strategy to achieve the goal of sustainable production.

Following worldwide research trends and policies, the use of reclaimed water or reuse of treated NS or wastewater from other activities is expected to be a great advance in the Mediterranean region in the next years, and, hopefully, becomes a generalized and safe practice in a region suffering with climate change and water shortage.

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Conflict of interest

The authors have no competing interests to declare.

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References

- [1] United Nations. Goals for Sustainable Development. 2015. Available from: <https://www.un.org/sustainabledevelopment/sustainable-consumption-production/>
- [2] Pardossi A, Tognoni F, Incrocci L. Mediterranean greenhouse technology. *Chronica Horticulturae*. 2004;**44**:28-34
- [3] Mariz-Ponte N, Martins S, Gonçalves A, Correia CM, Ribeiro C, Santos MDC. The potential use of the UV-A and UV-B to improve tomato quality and preference for consumers. *Scientia Horticulturae*. 2019;**246**:777-784. DOI: 10.1016/j.scienta.2018.11.058
- [4] FAO. Countries by Commodity. 2023. Available from: https://www.fao.org/faostat/en/#rankings/countries_by_commodity
- [5] CONFAGRI. Como vai mudar o mercado agrícola europeu até 2030?, 2018, available from: <https://www.confagri.pt/vai-mudar-mercado-agricola-europeu-ate-2030/>
- [6] Paulo Maria. Personal communication, Hortomaria, Torres vedras. 2019
- [7] Gruda N, Tanny J. Protected crops – Recent advances, innovative technologies and future challenges. *Acta Horticulturae*. 2015;**1107**:271-278. DOI: 10.17660/ActaHortic.2015.1107.37
- [8] FAO. Plant Production and Protection Paper 230- Good Agricultural Practices for greenhouse vegetable production in the South East European countries. 2017. ISSN 2070-2515
- [9] Muñoz P, Antón A, Nuñez M, Paranjpe A, Ariño J, Castells X, et al. Comparing the environmental impacts of greenhouse versus open-field tomato production in the Mediterranean region. *GreenSys 2007: High Technology for Greenhouse System Management*. Italy: Naples. 3-6 Oct 2007;**1**:1591-1596
- [10] Baptista F, Murcho D, Silva L. Assessment of Energy Consumption in Greenhouse Tomato Production in the West Region of Portugal. Portugal: Greensys; 2015
- [11] Ferreira VS. Avaliação das condições climáticas em dois tipos de estufa e sua influência na produtividade e nos custos de produção do tomate, na região do Oeste, Master Thesis. ISA: Ullisboa; 2017
- [12] Salazar R, Rojano AAL. New technologies in tomato greenhouse production. In: *Proceedings International Conference of Agricultural Engineering*. Zurich: EURAGENG; 2014
- [13] Hochmuth GJ. Production of Greenhouse Tomatoes - Florida Greenhouse Vegetable Production Handbook. 2018. Vol. 3. Available from: <http://edis.ifas.ufl.edu/pdf/CV/CV26600.pdf>
- [14] European Scientists. Position Paper on the ECJ Ruling on CRISPR. 2018. Available from: www.vib.be/en/news/Documents/
- [15] European Scientists. Letter to President Juncker on Genome Editing. 2019. Available from: <http://www.vib.be>
- [16] Schwarz D, Öztekin GB, Tüzel Y, Brückner B, Krumbein A. Rootstocks can enhance tomato growth and quality characteristics at low potassium supply. *Scientia Horticulturae*. 2013;**149**:70-79. DOI: 10.1016/j.scienta.2012.06.013

- [17] Bai M, Chen W, Xie B, Yang G. A novel strategy to enhance resistance to cucumber mosaic virus in tomato by grafting to transgenic rootstocks. *Journal of Integrative Agriculture*. 2016;**15**(9):2040-2048. DOI: 10.1016/S2095-3119(16)61330-8
- [18] Asins MJ, Albacete A, Martínez-Andujar C, Pérez-Alfocea F, Dieleman JA. Genetic analysis of rootstock-mediated nitrogen (N) uptake and root-to-shoot signalling at contrasting N availabilities in tomato. *Plant Science*. 2017;**263**:94-106. DOI: 10.1016/j.plantsci.2017.06.012
- [19] Cantero-Navarro E, Romero-Aranda R, Fernández-Muñoz R, Martínez-Andujar C, Albacete A. Improving agronomic water use efficiency in tomato by rootstock-mediated hormonal regulation of leaf biomass. *Plant Science*. 2016;**251**:90-100. DOI: 10.1016/j.plantsci.2016.03.001
- [20] Hanna HY. Influence of cultivar, growing media, and cluster pruning on greenhouse tomato yield and fruit quality. *HortThechnology*. 2009;**19**(2):395-399. DOI: 10.21273/HORTSCI.19.2.395
- [21] Zhang X, You S, Tian Y, Li J. Comparison of plastic film, biodegradable paper and bio-based film mulching for summer tomato production: Soil properties, plant growth, fruit yield and fruit quality. *Scientia Horticulturae*. 2019;**249**:38-48. DOI: 10.1016/j.scienta.2019.01.037
- [22] Xiaohui F, Kai G, Ce Y, Jinsong L, Huanyu C, Xiaojing L. Growth and fruit production of tomato grafted onto wolfberry (*Lycium chinense*) rootstock in saline soil. *Scientia Horticulturae*. 2019;**255**:298-305. DOI: 10.1016/j.scienta.2019.05.028
- [23] Bello TT, Fawole B, Claudius-Cole A. Management of Root-Knot Nematodes (*Meloidogyne* Spp) on tomato using antagonistic plants. *Journal of Biology, Agriculture and Healthcare*. 2014;**4**(24):97-101
- [24] Gómez-Tenorio MA, Tello JC, Zanón MJ, de Cara M. Soil disinfestation with dimethyl disulfide (DMDS) to control *Meloidogyne* and *Fusarium oxysporum* f. sp. *radicis-lycopersici* in a tomato greenhouse. *Crop Protection*. 2018;**112**:133-140. DOI: 10.1016/j.cropro.2018.05.023
- [25] Chellemi DO, Roskopf EN. Yield potential and soil quality under alternative crop production practices for fresh market pepper. *Renewable Agriculture and Food Systems*. 2004;**19**:168-175. DOI: 10.1079/RAFS200479
- [26] Miller SA. The Ohio State University. Managing Diseases of Organic Tomatoes in Greenhouses and High Tunnels. 2018. Available from: <https://eorganic.org/node/3069>
- [27] Matthiessen JN, Kirkegaard JA. Biofumigation and enhanced biodegradation: Opportunity and challenge in soilborne pest and disease management. *Critical Reviews in Plant Sciences*. 2006;**25**:235-265. DOI: 10.1080/07352680600611543
- [28] Mauro RP, Lo Monaco A, Lombardo S, Restuccia A, Mauromicale G. Eradication of *Orobanche/Phelipanche* spp. seedbank by soil solarization and organic supplementation. *Scientia Horticulturae*. 2015;**193**:62-68. DOI: 10.1016/j.scienta.2015.06.038
- [29] Selina P, Bledsoe ME. U.S. Greenhouse/Hothouse Hydroponic Tomato Timeline. Raleigh, NC 27606: Village Farms, L.P; 2002. Available from: <https://ipmdata.ipmcenters.org>

- [30] Lopez-Galvez F, Allende A, Pedrero-Salcedo F, Alarcon JJ, Gil MI. Safety assessment of greenhouse hydroponic tomatoes irrigated with reclaimed and surface water. *International Journal of Food Microbiology*. 2014;**191**:97-102. DOI: 10.1016/j.ijfoodmicro.2014.09.004
- [31] Papadopoulos AP. Growing Greenhouse Tomatoes in Soil and in Soilless Media. Ontario, Canada: Publ. 1865/E, Communi. Branch, Agriculture and Agri-food; 1991
- [32] Dannehl D, Suhl J, Ulrichs C, Schmidt U. Evaluation of substitutes for rock wool as growing substrate for hydroponic tomato production. *Journal of Applied Botany and Food Quality*. 2015;**88**:68-77. DOI: 10.5073/JABFQ.2015.088.010
- [33] Kaur H. Development of Hydroponic System for Greenhouse Tomato, Master Thesis in Soil and Water Engineering. Punjab: Punjab Agricultural University; 2016
- [34] Valenzano V, Parente A, Serio F, Santamaria P. Effect of growing system and cultivar on yield and water-use efficiency of greenhouse-grown tomato. *Journal of Horticultural Science & Biotechnology*. 2008;**83**(1):71-75
- [35] Almaghrabi OA, Massoud SI, Abdelmoneim TS. Influence of inoculation with plant growth promoting rhizobacteria (PGPR) on tomato plant growth and nematode reproduction under greenhouse conditions. *Saudi Journal of Biological Sciences*. 2013;**20**(1):57-61. DOI: 10.1016/j.sjbs.2012.10.004
- [36] Punja ZK, Rodriguez G, Tirajoh A. Effects of *Bacillus subtilis* strain QST 713 and storage temperatures on post-harvest disease development on greenhouse tomatoes. *Crop Protection*. 2016;**84**:98-104. DOI: 10.1016/j.cropro.2016.02.011
- [37] Gravel V, Antoun H, Tweddell RJ. Growth stimulation and fruit yield improvement of greenhouse tomato plants by inoculation with *Pseudomonas putida* or *Trichoderma atroviride*: Possible role of indole acetic acid (IAA). *Soil Biology and Biochemistry*. 2007;**39**(8):1968-1977. DOI: 10.1016/j.soilbio.2007.02.015
- [38] Yim W, Seshadri S, Kim K, Lee G, Sa T. Ethylene emission and PR protein synthesis in ACC deaminase producing *Methylobacterium* spp. inoculated tomato plants (*Lycopersicon esculentum* mill.) challenged with *Ralstonia solanacearum* under greenhouse conditions. *Plant Physiology and Biochemistry*. 2013;**67**:95-104. DOI: 10.1016/j.plaphy.2013.03.002
- [39] Delaplane KS, Mayer DR, Mayer DF. Crop Pollination by Bees. Wallingford: CABI Publishing; 2000. p. 352. ISBN: 085199783X, 9780851997834
- [40] Almeida L, Amaro F, Figueiredo E, Godinho MC, Mexia A, Nunes AP. Melhoria da produção hortícola em estufa na região oeste. 1999. Available from: <http://www.cothn.pt>
- [41] Borges JCMC. *Bombus terrestris* e *Bombus* spp; Captura, Identificação das Espécies, Subespécies e Castas, Ciclo de Vida e Dinâmica Populacional das Populações Selvagens, Master Thesis. Porto: FC da Universidade do Porto; 2018
- [42] Kapongo JP, Shipp L, Kevan P, Sutton JC. Co-vectoring of *Beauveria bassiana* and *Clonostachys rosea* by bumble bees (*Bombus impatiens*) for control of insect pests and suppression of grey mould in greenhouse tomato and sweet pepper. *Biological Control*. 2008;**46**(3):508-514. DOI: 10.1016/j.biocontrol.2008.05.008

- [43] Seabra SG, Silva SE, Nunes VL, Sousa VC, Martins J, Marabuto E, et al. Genomic signatures of introgression between commercial and native bumblebees, *Bombus terrestris*, in western Iberian Peninsula – Implications for conservation and trade regulation. *Evolutionary Applications*. 2018;**12**(4):679-691. DOI: 10.1111/eva.12732
- [44] Jarquín-Enríquez L, Mercado-Silva EM, Maldonado JL, Lopez-Baltazar J. Lycopene content and color index of tomatoes are affected by the greenhouse cover. *Scientia Horticulturae*. 2013;**155**:43-48. DOI: 10.1016/j.scienta.2013.03.004
- [45] Kavga A, Souliotis M, Koumoulose EP, Fokaides PA, Charitidis CA. Environmental and nanomechanical testing of an alternative polymer nanocomposite greenhouse covering material. *Solar Energy*. 2018;**159**:1-9. DOI: 10.1016/j.solener.2017.10.073
- [46] Geoola F, Kashti Y, Levi A, Brickman R. Quality evaluation of antidrop properties of greenhouse cladding materials. *Polymer Testing*. 2004;**23**:755-761. DOI: 10.1016/j.polymertesting.2004.04.006
- [47] Tantau HJ, Hinken J, von Elsner B, Max JFJ, Ulbrich A, Schurr U, et al. Solar transmittance of greenhouse covering materials. *Acta Horticulturae*. 2012;**956**:441-448. DOI: 10.17660/ActaHortic.2012.956.51
- [48] Emekli NY, Büyüktaş K, Başçetinçelik A. Changes of the light transmittance of the LDPE films during the service life for greenhouse application. *Journal of Building Engineering*. 2016;**6**:126-132. DOI: 10.1016/j.jobbe.2016.02.013
- [49] Alsadon A, Al-Helal I, Ibrahim A, Abdel-Ghany A, Al-Zaharani S, Ashour T. The effects of plastic greenhouse covering on cucumber (*Cucumis sativus* L.) growth. *Ecological Engineering*. 2015;**87**:305-312. DOI: 10.1016/j.ecoleng.2015.12.005
- [50] Max JFJ, Schurr U, Tantau HJ, Mutwiwa UN, Hofmann T, Ulbrich A. Greenhouse Cover Technology in Horticultural Reviews. In: Jules J, editor. Wiley- Blackwell. 2012;**40**. DOI: 10.1002/9781118351871.ch7. ISBN: 9781118345832
- [51] Aldaftari HA, Okajima J, Komiya A, Maruyama S. Radiative control through greenhouse covering materials using pigmented coatings. *Journal of Quantitative Spectroscopy and Radiative Transfer*. 2019;**231**:29-36. DOI: 10.1016/j.jqsrt.2019.04.009
- [52] Xie X, Liu YJ, Hao JJ, Ju L, Du WC, Yang HW. Feasibility study of a new solar greenhouse covering material. *Journal of Quantitative Spectroscopy and Radiative*. 2019;**224**:37-43. DOI: 10.1016/j.jqsrt.2018.11.004
- [53] Al-Mahdouri A, Gonome H, Okajima J, Maruyama S. Theoretical and experimental study of solar thermal performance of different greenhouse cladding materials. *Solar Energy*. 2014;**107**:314-327. DOI: 10.1016/j.solener.2014.05.006
- [54] Castilla N, Baeza E. Greenhouse Site Selection, Chap.2. Rome: FAO Paper 217, Food and Agriculture Organization of the United Nations; 2013
- [55] Kwon JK, Khoshimkhujaev B, Lee JH, Yu IH, Park KS, Choi HG. Growth and yield of tomato and cucumber plants in polycarbonate or glass greenhouses. *Korean Journal of Horticultural Science and Technology*. 2017;**35**(1):79-87. DOI: 10.12972/kjhst.20170009

- [56] Živanović B, Vidović M, Komić SM, Jovanović L, Kolarž P, Morina F, et al. Contents of phenolics and carotenoids in tomato grown under polytunnels with different UV-transmission rates. *Turkish Journal of Agriculture and Forestry*. 2017;**41**(2):113-120. DOI: 10.3906/tar-1612-56
- [57] Murakami K, Fukuoka N, Noto S. Improvement of greenhouse microenvironment and sweetness of melon (*Cucumis melo* L.) fruits by greenhouse shading with a new kind of near-infrared ray-cutting net in mid-summer. *Scientia Horticulturae*. 2018;**218**:1-7. DOI: 10.1016/j.scienta.2017.02.011
- [58] Kittas C, Katsoulas N, Rigakis N, Bartzanas T, Kitta E. Effects on microclimate, crop production and quality of a tomato crop grown under shade nets. *The Journal of Horticultural Science and Biotechnology*. 2012;**87**:7-12. DOI: 10.1080/14620316.2012.11512822
- [59] Smith GB, Gentle A, Swift PD, Earp A, Mronga N. Coloured paints based on iron oxide and silicon oxide coated flakes of aluminium as the pigment, for energy efficient paint: Optical and thermal experiments. *Solar Energy Materials & Solar Cells*. 2003;**79**(2):179-197. DOI: 10.1016/S0927-0248, (02)00410-5
- [60] Seven SA, Tastan ÖF, Tas CE, Ünal H, Ince İA, Menciloglu YZ. Insecticide-releasing LLDPE films as greenhouse cover materials. *Materials Today Communications*. 2019;**19**:170-176. DOI: 10.1016/j.mtcomm.2019.01.015
- [61] Jiang C, Johkan M, Hohjo M, Tsukagoshi S, Maruo T. Photosynthesis, plant growth, and fruit production of single-truss tomato improves with supplemental lighting provided from underneath or within the inner canopy. *Scientia Horticulturae*. 2017;**222**:221-229
- [62] Kowalczyk K, Gajc-Wolska J, Metera A, Mazur K, Radzanowska J, Szatkowski M. Effect of supplemental lighting on the quality of tomato fruit (*Solanum lycopersicum* M L.) in autumn-winter cultivation. *Acta Horticulturae*. 2012;**956**:395-401. DOI: 10.17660/ActaHortic.2012.956.46
- [63] Hao X, Little C, Zheng JM, Cao R. Far-red LEDs improve fruit production in greenhouse tomato grown under high-pressure sodium lighting. *Acta Horticulturae*. 2016;**1134**:95-102. DOI: 10.17660/ActaHortic.2016.1134.13
- [64] Zhang YT, Zhang YQ, Yang QC, Li T. Overhead supplemental far-red light stimulates tomato growth under intra-canopy lighting with LEDs. *Journal of Integrative Agriculture*. 2019;**18**(1):62-69. DOI: 10.1016/S2095-3119(18)62130-6
- [65] Fanwoua J, Vercambre G, Buck-Sorlin G, Dieleman JA, Génard M. Supplemental LED lighting affects the dynamics of tomato fruit growth and composition. *Scientia Horticulturae*. 2019;**256**:108571. DOI: 10.1016/j.scienta.2019.108571
- [66] Mitchell C, Dzakovich M, Gomez C, Lopez R, Burr J, Hernández R, et al. Light-emitting diodes in horticulture. *Horticultural Reviews*. 2015;**43**:1-88. DOI: 10.1002/9781119107781.ch01
- [67] Dzakovich MP, Gómez C, Mitchell CA. Tomatoes grown with light-emitting diodes or high-pressure sodium supplemental lights have similar fruit-quality attributes. *HortScience*. 2015;**50**:1498-1502. DOI: 10.21273/HORTSCI.50.10.1498
- [68] Deram P. Light-Emitting-Diode (LED) Lighting for Greenhouse Tomato Production, Master thesis, McGill University; Montreal, 2013

- [69] Christie JM. Phototropin blue-light receptors. *Annual Review of Plant Biology*. 2007;**58**:21-45. DOI: 10.1146/annurev.arplant.58.032806.103951
- [70] O'Carrigan A, Hinde E, Lu N, Xu XQ, Duan H, Huang G, et al. Effects of light irradiance on stomatal regulation and growth of tomato. *Environmental and Experimental Botany*. 2014;**98**:65-73. DOI: 10.1016/j.envexpbot.2013.10.007
- [71] Smith HL, McAusland L, Murchie EH. Don't ignore the green light: Exploring diverse roles in plant processes. *Journal of Experimental Botany*. 2017;**68**:2099-2110. DOI: 10.1093/jxb/erx098
- [72] Lin KH, Huang MY, Huang WD, Hsu MH, Yang ZW, Yang CM. The effects of red, blue, and white light-emitting diodes on the growth, development, and edible quality of hydroponically grown lettuce (*Lactuca sativa* L. var. capitata). *Scientia Horticulturae*. 2013;**150**:86-91. DOI: 10.1016/j.scienta.2012.10.002
- [73] Kaiser E, Weerheim K, Schipper R, Dieleman JA. Partial replacement of red and blue by green light increases biomass and yield in tomato. *Scientia Horticulturae*. 2019;**249**:271-279. DOI: 10.1016/j.scienta.2019.02.005
- [74] Schouten RE, Woltering EJ, Tijskens LMM. Sugar and acid interconversion in tomato fruits based on biopsy sampling of locule gel and pericarp tissue. *Postharvest Biology and Technology*. 2016;**111**:83-92. DOI: 10.1016/j.postharvbio.2015.07.032
- [75] Kim HJ, Yang T, Choi S, Wang YJ, Lin MY, Liceaga AM. Supplemental intracanopy far-red radiation to red LED light improves fruit quality attributes of greenhouse tomatoes. *Scientia Horticulturae*. 2020;**261**:108985. DOI: 10.1016/j.scienta.2019.108985
- [76] Gómez C, Mitchell CA. In search of an optimized supplemental lighting spectrum for greenhouse tomato production with intracanopy lighting. *Acta Horticulturae*. 2016;**1134**:57-62. DOI: 10.17660/ActaHortic.2016.1134.8
- [77] Li Q, Liu Y, Tian S, Liang Z, Li S, Li Y, et al. Effect of supplemental lighting on water transport, photosynthetic carbon gain and water use efficiency in greenhouse tomato. *Scientia Horticulturae*. 2019;**256**:108630. DOI: 10.1016/j.scienta.2019.108630
- [78] Lu N, Maruo T, Johkan M, Hohjo M, Tsukagoshi S, Ito Y, et al. Effects of supplemental lighting with light-emitting diodes (LEDs) on tomato yield and quality of single-truss tomato plants grown at high planting density environ. *Control Biology*. 2012;**50**(1):63-74. DOI: 10.2525/ecb.50.63
- [79] Grozeff GEG, Senn ME, Alegre ML, Chaves AR, Bartoli CG. Nocturnal low irradiance pulses improve fruit yield and lycopene concentration in tomato. *Scientia Horticulturae*. 2016;**203**:47-52. DOI: 10.1016/j.scienta.2016.03.001
- [80] De Pascale S, Maggio A. Sustainable protected cultivation at Mediterranean climate, perspectives and challenges. *Acta Horticulturae*. 2004;**691**:29-42. DOI: 10.17660/ActaHortic.2005.691.1
- [81] Shen Y, Wei R, Xu L. Energy consumption prediction of a greenhouse and optimization of daily average temperature. *Energies*. 2018;**11**:65. DOI: 10.3390/en11010065
- [82] Baptista FJ, Briassoulis D, Stanghellini C, Silva LL, Balafoutis AT, Meyer-Aurich A, et al. Energy efficiency In tomato greenhouse production - a

preliminary study. *Acta Horticulturae*. 2014;**1037**:179-185. DOI: 10.17660/ActaHortic.2014.1037.18

[83] Gourdo L, Fatnassi H, Tiskatine R, Wifaya A, Demrati H, Aharoune A, et al. Solar energy storing rock-bed to heat an agricultural greenhouse. *Energy*. 2019;**169**:206-212. DOI: 10.1016/j.energy.2018.12.036

[84] Ntinis GK, Koukounaras A, Kotsopoulos T. Effect of energy saving solar sleeves on characteristics of hydroponic tomatoes grown in a greenhouse. *Scientia Horticulturae*. 2015;**194**:126-133. DOI: 10.1016/j.scienta.2015.08.013

[85] Bazgaou A, Fatnassi H, Bouharroud R, Ezzaeri K, Gourdo L, Wifaya A, et al. Effect of active solar heating system on microclimate, development, yield and fruit quality in greenhouse tomato production. *Renewable Energy*. 2021;**165**(Part 1):237-250. DOI: 10.1016/j.renene.2020.11.007

[86] Gourdo L, Fatnassi H, Bouharroud R, Ezzaeri K, Bazgaou A, Wifaya A, et al. Heating canarian greenhouse with a passive solar water-sleeve system: Effect on microclimate and tomato crop yield. *Solar Energy*. 2019;**188**:1349-1359. DOI: 10.1016/j.solener.2019.07.004

[87] Mobtaker HG, Ajabshirchi Y, Ranjbar F, Matloobi M. Solar energy conservation in greenhouse: Thermal analysis and experimental validation. *Renewable Energy*. 2016;**96**:509-519. DOI: 10.1016/j.renene.2016.04.079

[88] Hassanien RHE, Li M, Yin F. The integration of semi-transparent photovoltaics on greenhouse roof for energy and plant production. *Renewable Energy*. 2018;**121**:377-388. DOI: 10.1016/j.renene.2018.01.044

[89] Callejón-Ferre AJ, Velázquez-Martí B, López-Martínez JA, Manzano-Agugliaro F. Greenhouse crop residues: Energy potential and models for the prediction of their higher heating value. *Renewable and Sustainable Energy Reviews*. 2011;**15**:948-955. DOI: 10.1016/j.rser.2010.11.012

[90] Kläring HP, Klopotek Y, Krumbein A, Schwarz D. The effect of reducing the heating set point on the photosynthesis, growth, yield and fruit quality in greenhouse tomato production. *Agricultural and Forest Meteorology*. 2015;**214**:178-188. DOI: 10.1016/j.agrformet.2015.08.250

[91] Baptista F. Modelling the Climate in Unheated Tomato Greenhouses and Predicting Botrytis Cinerea Infection. Doctoral Thesis. Évora: Évora University; 2007

[92] Kumar KS, Jha MK, Tiwari KN, Singh A. Modeling and evaluation of greenhouse for floriculture in subtropics. *Energy and Buildings*. 2010;**42**(7):1075-1083. DOI: 10.1016/j.enbuild.2010.01.021

[93] Qian T. Crop Growth and Development in Closed and Semi-Closed Greenhouses. Wageningen, NL: Wageningen University; 2017. p. 112. PhD thesis

[94] Zhang Z, Gates R, Zhirong Z, Xiaohui H. Evaluation of ventilation performance and energy efficiency of greenhouse fans. *International Journal of Agricultural and Biological Engineering*. 2015;**8**:103. DOI: 10.3965/j.ijabe.20150801.014

[95] Hou H, Chen H, Cai H, Yang F, Wang F. CO₂ and N₂O emissions from Lou soils of greenhouse tomato fields under aerated irrigation. *Atmospheric Environment*. 2016;**132**:69-76. DOI: 10.1016/j.atmosenv.2016.02.027

- [96] Li Y, Niu W, Dyck M, Wang J, Zou X. Yields and nutritional of greenhouse tomato in response to different soil aeration Vol. at two depths of subsurface drip irrigation. *Scientific Reports*. 2016;**6**:39307
- [97] Chen H, Hou HJ, Wang XY, Zhu Y, Cai H. The effects of aeration and irrigation regimes on soil CO₂ and N₂O emissions in a greenhouse tomato production system. *Journal of Integrative Agriculture*. 2018;**17**(2):449-460. DOI: 10.1016/S2095-3119(17)61761-1
- [98] Du YD, Gu XB, Wang JW, Niu WQ. Yield and gas exchange of greenhouse tomato at different nitrogen levels under aerated irrigation. *Science of the Total Environment*. 2019;**668**(10):1156-1164. DOI: 10.1016/j.scitotenv.2019.03.098
- [99] Zhang Z, Liu L, Zhang M, Zhang Y, Wang Q. Effect of carbon dioxide enrichment on health-promoting compounds and organoleptic properties of tomato fruits grown in greenhouse. *Food Chemistry*. 2014;**153**:157-163. DOI: 10.1016/j.foodchem.2013.12.052
- [100] Jin C, Du S, Wang Y, Condon J, Lin X, Zhang Y. Carbon dioxide enrichment by composting in greenhouses and its effect on vegetable production. *Journal of Plant Nutrition and Soil Science*. 2009;**172**:418-424. DOI: 10.1002/jpln.200700220
- [101] Marchi B, Zanoni S, Pasetti M. Industrial Symbiosis for greener horticulture practices: The CO₂ enrichment from energy intensive industrial processes. *Procedia CIRP*. 2018;**69**:562-567. DOI: 10.1016/j.procir.2017.11.117
- [102] Stanghellini C, Kempkes F. Steering of fogging: Control of humidity, temperature or transpiration? *Acta Horticulturae*. 2008;**797**:61-67. DOI: 10.17660/ActaHortic.2008.797.6
- [103] Leyva R, Constán-Aguilar C, Sánchez-Rodríguez E, Romero-Gámez M, Soriano T. Cooling systems in screenhouses: Effect on microclimate, productivity and plant response in a tomato crop. *Biosystems Engineering*. 2015;**129**:100-111. DOI: 10.1016/j.biosystemseng.2014.09.018
- [104] Abdel-Ghany AM, Kozai T. Cooling efficiency of fogging Systems for Greenhouses. *Biosystems Engineering*. 2006;**94**:97-109. DOI: 10.1016/j.biosystemseng.2006.02.008
- [105] Kaneda Y, Ibayashi H, Oishi N, Mineno H. Greenhouse environmental control system based on SW-SVR. *Procedia Computer Science*. 2015;**60**:860-869. DOI: 10.1016/j.procs.2015.08.249
- [106] Kurose T. Tomato king Kagome leads with high-tech greenhouses. In *Nikkei Asian Review*. 2016. Available from: <https://asia.nikkei.com/Business/Biotechnology/>
- [107] Meric MK, Tuzel IH, Tuzel Y, Oztekin GB. Effects of nutrition systems and irrigation programs on tomato in soilless culture. *Agricultural Water Management*. 2011;**99**(1):19-25. DOI: 10.1016/j.agwat.2011.08.004
- [108] Massa D, Incrocci L, Maggini R, Bibbiani C, Pardossi A. Simulation of crop water and mineral relations in greenhouse soilless culture. *Environmental Modelling & Software*. 2011;**26**(6):711-722. DOI: 10.1016/j.envsoft.2011.01.004
- [109] Kondo N, Yata K, Iida M, Shiigi T, Omori H. Development of an end-effector for a tomato cluster harvesting robot. *Engineering in Agriculture, Environment and Food*.

2014;**3**(1):20-24. DOI: 10.1016/S1881-8366(10)80007-2

[110] Metomotion. GRoW - Greenhouse Robotic Worker. 2018. Available from: <https://metomotion.com/>

[111] Li Z, Miao F, Yang Z, Chai P, Yang S. Factors affecting human hand grasp type in tomato fruit-picking: A statistical investigation for ergonomic development of harvesting robot. *Computers and Electronics in Agriculture*. 2019;**157**:90-97. DOI: 10.1016/j.compag.2018.12.047

[112] Li Z, Li P, Liu J. Physical and mechanical properties of tomato fruits as related to robot's harvesting. *Journal of Food Engineering*. 2011;**103**(2):170-178. DOI: 10.1016/j.jfoodeng.2010.10.013

[113] García-Luna F, Morales-Díaz A. Towards an artificial vision-robotic system for tomato identification. *IFAC-PapersOnLine*. 2016;**49**(16):365-370

[114] Rincón VJ, Grella M, Marucco P, Alcatrão LE, Sanchez-Hermosilla J, Balsari P. Spray performance assessment of a remote-controlled vehicle prototype for pesticide application in greenhouse tomato crops. *Science of the Total Environment*. 2020;**726**:138509. DOI: 10.1016/j.scitotenv.2020.138509

[115] Gerçek S, Demirkaya M, Işık D. Water pillow irrigation versus drip irrigation with regard to growth and yield of tomato grown under greenhouse conditions in a semi-arid region. *Agricultural Water Management*. 2017;**180**:172-177. DOI: 10.1016/j.agwat.2016.11.012

[116] Li Y, Wang L, Xue X, Guo W, Chen F. Comparison of drip fertigation and negative pressure fertigation on soil water dynamics and water use efficiency of greenhouse tomato grown

in the North China plain. *Agricultural Water Management*. 2017;**184**:1-8. DOI: 10.1016/j.agwat.2016.12.018

[117] Li X, Xie YG, Wang GD, Xue XZ. Growth and physiological characteristics of eggplant under negative hydraulic head irrigation in greenhouse. *Natural Sciences Education*. 2016;**44**:163-169. DOI: 10.3389/fpls.2015.00262

[118] Li S, Xue XZ, Guo WS, Li X, Chen F. Effects of water supply tension on yield and water use efficiency of greenhouse cucumber. *Scientia Agricultura Sinica*. 2010;**43**:337-345. DOI: 10.3864/j.issn.0578-1752.2010.02.014

[119] Yang L, Qu H, Zhang Y, Li F. Effects of partial root-zone irrigation on physiology, fruit yield and quality and water use efficiency of tomato under different calcium levels. *Agricultural Water Management*. 2012;**104**:89-94. DOI: 10.1016/j.agwat.2011.12.001

[120] Montesano F, Parente A, Santamaria P. Closed cycle subirrigation with low concentration nutrient solution can be used for soilless tomato production in saline conditions. *Scientia Horticulturae*. 2010;**124**:338-344. DOI: 10.1016/j.scienta.2010.01.017

[121] Cliff MA, Li JB, Toivonen PMA, Ehret DL. Effects of nutrient solution electrical conductivity on the compositional and sensory characteristics of greenhouse tomato fruit. *Postharvest Biology and Technology*. 2012;**74**:132-140. DOI: 10.1016/j.postharvbio.2011.12.007

[122] Rosberga AK, Gruyerb N, Hultberga M, Wohankac W, Alsanius BW. Monitoring rhizosphere microbial communities in healthy and *Pythium ultimum* inoculated tomato plants in soilless growing systems.

- Scientia Horticulturae. 2014;**173**(27):106-113. DOI: 10.1016/j.scienta.2014.04.036
- [123] Dannehl D, Schuch I, Gao Y, Cordiner S, Schmidt U. Hypochlorite application for controlling algae biofilm formation, microorganisms and tomato production in recirculating systems. *Gesunde Pflanz.* 2015;**67**:191-199. DOI: 10.1007/s10343-015-0351-3
- [124] Dorais M, Dorval R, Demers DA, Micevic D, Turcotte G, Hao X, et al. Improving tomato fruit quality by increasing salinity: Effects on ion uptake, growth and yield. *Acta Horticulturae.* 2000;**511**:185-195. DOI: 10.17660/ActaHortic.2000.511.21
- [125] Fabre MD, Jeannequin B. Effect of the salinity on the organoleptic quality and yield of early-grown soilless grafted tomatoes under heated glasshouses in the south of France. *Cahiers Agricultures.* 2011;**20**:266-273
- [126] Daliakopoulos N, Apostolakis A, Wagner K, Deligianni A, Tsanis IK. Effectiveness of *Trichoderma harzianum* in soil and yield conservation of tomato crops under saline irrigation. *Catena.* 2019;**175**:144-153. DOI: 10.1016/j.catena.2018.12.009
- [127] Favati F, Lovelli S, Galgano F, Miccolis V, Tommaso T, Candido V. Processing tomato quality as affected by irrigation scheduling. *Scientia Horticulturae.* 2009;**122**:562-571. DOI: 10.1016/j.scienta.2009.06.026
- [128] Chen J, Kang S, Du T, Qiu R, Guo P, Chen R. Quantitative response of greenhouse tomato yield and quality to water deficit at different growth stages. *Agricultural Water Management.* 2013;**129**:152-162. DOI: 10.1016/j.agwat.2013.07.011
- [129] Galindo A, Collado-González J, Griñán I, Corell M, Centeno A, Palomo MJ, et al. Deficit irrigation and emerging fruit crops as a strategy to save water in Mediterranean semiarid agrosystems. *Agricultural Water Management.* 2018;**202**:311-324. DOI: 10.1016/j.agwat.2017.08.015
- [130] Coyago-Cruz E, Meléndez-Martínez AJ, Moriana A, Girón IF, Corell M. Yield response to regulated deficit irrigation of greenhouse cherry tomatoes. *Agriculture Water Management.* 2019;**213**:212-221. DOI: 10.1016/j.agwat.2018.10.020
- [131] Wang F, Kang S, Du T, Li F, Qiu R. Determination of comprehensive quality index for tomato and its response to different irrigation treatments. *Agricultural Water Management.* 2011;**98**(8):1228-1238. DOI: 10.1016/j.agwat.2011.03.004
- [132] Ministry of Health, state of Israel. Irrigation with Treated Wastewater. 2021. Available from: www.health.gov.il/English/Topics/EnviroHealth/Reclaimed_Water/
- [133] Delaide B, Teerlinck S, Decombel A, Bleyaert P. Effect of wastewater from a pikeperch (*Sander lucioperca* L.) recirculated aquaculture system on hydroponic tomato production and quality. *Agricultural Water Management.* 2019;**226**:105814. DOI: 10.1016/j.agwat.2019.105814
- [134] Magwaza ST, Magwaza LS, Odindo AO, Mditshwa A, Buckley C. Partially treated domestic wastewater as a nutrient source for tomatoes (*Lycopersicum solanum*) grown in a hydroponic system: Effect on nutrient absorption and yield. *Heliyon.* 2020;**6**:e05745. DOI: 10.1016/j.heliyon.2020.e05745
- [135] Magwaza ST, Magwaza LS, Odindo AO, Mditshwa A, Buckley C.

Evaluating the feasibility of human excreta-derived material for the production of hydroponically grown tomato plants - part II: Growth and yield. *Agricultural Water Management*. 2020;234:106115. DOI: 10.1016/j.agwat.2020.106115

[136] Tomatinov. Acções. 2018. Available from: <https://tomatinov.wordpress.com/>

[137] Agrotec. Terraguar apresenta sistema inovador em Portugal para a produção de tomate em estufa, em sistema fechado. 2020. Available from: <http://www.agrotec.pt>