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Review

Energy and Water Related Parameters in Tomato and Cucumber Greenhouse Crops in Semiarid Mediterranean Regions. A Review, Part II: Irrigation and Fertigation

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Abstract: Increasing agricultural systems' resource efficiency is the key action for producing adequate food quantities in semi-arid Mediterranean regions while coping with water scarcity, environmental constraints and economic issues. Optimisation of irrigation and fertigation practices imposes different approaches, considering plant-water-soil relationships based on prevailing greenhouse microclimatic conditions, ensuring optimal production per drop of water and unit of fertiliser. In the content of "precision agricultural farming systems", nutrient uptake modelling, phyto-sensing, smart and sustainable technologies must be applied for monitoring and evaluating water and nutrients crops supply. However, in many cases, the use of irrigation and fertigation recipes given in the literature may not be compatible in the Mediterranean, as they usually originated based on northern European climatic conditions. The objective of this work is an attempt to understand various aspects of irrigation and fertigation management in vegetable fruiting crops such as tomato and cucumber towards nutrients and water resource sustainability in Mediterranean greenhouses.

Keywords: fertilisation; microirrigation; ferti(irri)gation; evapotranspiration; nutrient uptake; crop modelling

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1. Introduction

The sustainability of irrigated agriculture in the semi-arid Mediterranean region is threatening by overexploitation of natural resources, and changes in agricultural land use. Agriculture is the dominant water consumer in the region accounting for 81% of total water use; it is particularly vulnerable to climate conditions due to its dependence, for most of the year, on adequate quantities of good-quality water [1,2]. The diet of people who have lived in the Mediterranean is high in vegetables and fruits and is considered by UNESCO as an "Intangible Cultural Heritage of Humanity" with multiple sustainable benefits. Tomato (*Solanum lycopersicum* L.) and cucumber (*Cucumis sativus* L.) are among the most popular consumable vegetables that are produced all year round in greenhouses and open fields.

Greenhouses have increased productivity with reduced inputs, including water and fertilisers. Lower indoor wind speeds and solar radiation values decreased evapotranspiration by 20 to 40%. For a field-grown tomato in Egypt, the ratio of product yield to water use increased from 3 kg m^{-3} to 17 kg m^{-3} in an unheated greenhouse and reached 45 kg m^{-3} in a soilless growing system [3]. Accordingly, the ratio of the total value of production to the total crop irrigation water supply in cucumber crops was estimated at 30.5€ m^{-3} and 4.7€ m^{-3}, respectively, for a greenhouse and an outdoor crop in Cyprus [4]. Recently, closed recirculation soilless based systems have gained increasing interest as an environmentally friendly cultivation technique. It is relevant that the water use of tomato plants in an open soilless based system in Spain was estimated at 28.8 L Kg^{-1}, as opposed to 14.06 L Kg^{-1} for a closed recirculating system in the Netherlands [5].

Greenhouses in the Mediterranean are often concentrated in relatively small agricultural areas often associated with environmental pollution-related problems (e.g., eutrophication). To cope with nitrate contamination of aquifers, Mediterranean countries in the EU (e.g., Greece, Spain, Italy, Cyprus) adopted nitrates directive 91/676/EEC complemented within the water framework directive 2000/60/EC. The Common EU Agricultural Policy (CAP) also promotes sustainable food production with climate-friendly practices and methods. Better water management could reduce fertiliser's use and the use of energy for pumping water from deep wells in dry regions [6]. Furthermore, under Eastern Mediterranean conditions, high energy consumption for greenhouse cooling and irrigation processes is needed. That has to do also with the significant amount of good-quality water, which is needed to be evaporated within the greenhouse air to alleviate the high radiation load [7].

The United Nations 2030 Agenda for the sustainable development and zero-pollution ambition complementing by 2050 a climate-neutrality goal is supporting adaptation to climate change and promoting circular economy. On the other hand, the use of non-conventional water resources for irrigation, such as treated wastewater (TWW), has gained acceptance as an economic and viable alternative that could replace water and nutrient requirements of crops, simultaneously releasing equal quantities of potable water for other uses (i.e., domestic) [8]. Indicatively, the European Union (EU) have recently adopted the EU 2020/74 regulation on the minimum requirements for water reuse, aiming at promoting TWW reuse in agriculture and ensuring environmental protection, human and animal health and simultaneously supporting adaptation to climate change and promoting circular economy. Strict quality criteria for TWW reuse and precautionary agricultural practices have been also set by international organisations (WHO, [9]) and adopted by several countries worldwide, while other countries are following their own regulations (i.e., Israel, United States, China). Currently, TWW is reused for the irrigation or fertigation of high-value crops including tomato and cucumber [10,11].

Considering the above facts and the United Nations agenda for adaptation to climate change and sustainable development promoting circular economy and zero-pollution, we acknowledge that greenhouse cultivation in the Mediterranean region faces unique challenges. The objective of this work was to make a better understanding of various aspects of irrigation and fertigation management of fruiting crops such as tomatoes and cucumbers widely grown in Mediterranean greenhouses towards nutrients and water resources sustainability.

2. Irrigation Scheduling

Rational and efficient irrigation practices need to be addressed by growers from the perspective of regional water resources sustainability. Pressurised irrigation systems and proper irrigation scheduling, can save water and labour with higher returns on investment. Today, irrigation based on preset time intervals (i.e., time clock scheduling) with an automatic irrigation controller unit and solenoid valves (i.e., electric on-off valve) is among the most common irrigation methods. However, a mismatch between water supply and transpiration (i.e., water needs) often occurs. A better method of increasing water application efficiency is to apply water several times during a cycle with a minimum amount of water and fertilisers instead of just one application by the end of the drying cycle (i.e., pulse time clock scheduling). Nevertheless, crop water stress cannot be completely avoided, even in the case where automatic irrigation controllers are used [12]. The concept of a closed-loop feedback irrigation control system is central to the water application efficiency with the use of simple sensors for climate, soil or substrate monitoring (such as the tensiometers, pyranometers) [13]. Neto et al. [14] proposed a real-time feedback irrigation control system for a tomato crop based on maintained drainage electrical conductivity

(EC) under preset limits (3 ± 0.8 dS m^{-1}). Recent developments in the field have led to commercialise irrigation scheduling based on greenhouse air vapour pressure deficit (VPD) values [15]. Automatically monitoring plants' actual responses to changes in water (i.e., sap-flow, stem micro-variations, leaf temperature) on a 24-h basis is an important component in greenhouse irrigation [16,17]. Precision agricultural irrigation systems such as microcontrollers, programmable logic controllers and crop/sensor interfaces, programmed to control specific tasks that are characterised by sequential evolution [18]. In light of recent events in precision agriculture systems, the application of the Internet of Things (IoT), considered challenges in terms of productivity, food security and sustainability by connecting people with things [19]. Relatively, Zamora-Izquierdo et al. [20] showed that savings between 30–80% in water and nutrient consumption could be obtained for a soilless tomato crop based on edge and cloud computing of a precision agriculture management platform. Similarly, Katsoulas et al. [21] developed a web-based irrigation scheduling algorithm considering greenhouse climatic conditions, substrate water content and water balance for scheduling irrigation.

The method for estimating crop evapotranspiration (i.e., crop water needs) based on Class-A evaporation pan and local crop coefficient values (Kc values) adopted and widely used due to its simplicity in many regions. Table 1 shows, the monthly and yearly evapotranspiration requirements for tomato and cucumber soil-based grown crops in Cyprus as estimated for different greenhouse types and outdoor crops [22]. These are average site-specific values and subsequently, they will vary depending on the region, cultural practices and crops cultivars. For example, in another Mediterranean climatic region (Almería, Spain) for a tomato autumn-spring growing cycle a value of 557 mm was reported [23].

Table 1. Tomato and cucumber monthly and yearly evapotranspiration requirements (mm) at Mediterranean latitudes (35° N, Cyprus) [22].

	Tomato			Cucumber		
	Greenhouse	**High Tunnel**	**Outdoor Crop**	**Greenhouse**	**High Tunnel**	**Outdoor Crop**
January	42	12	-	42	12	-
February	60	24	-	48	24	-
March	85	60	-	72	40	-
April	120	90	15	120	60	15
May	180	120	75	208	104	75
June	168	156	150	-	50	170
July	-	-	168	-	-	216
August	-	-	168	-	-	-
September	-	-	78	-	-	-
October	12	-	-	-	-	-
November	40	-	-	40	-	-
December	36	-	-	36	-	-
Total	743	462	654	566	290	476

The length of the usual growth cycle for greenhouse tomato and cucumber in the Mediterranean region is considered 34 and 26 weeks, respectively.

However, a significant amount of water for the operation of active cooling systems in greenhouses should also be considered, as many times exceeds the water consumed by the plant [24]. For example, in a spring-summer cucumber crop under Mediterranean climatic conditions, the measured daily water evaporation through a wetted pad was between 2.1 and 2.9 L per m^{-2} of greenhouse floor area [7]. In another case, a forced-air ventilation system raised evaporation between 3.2 and 10.1 L per m^{-2} of the greenhouse floor [25].

Much consideration has been given in evapotranspiration models for the accurate irrigation, simulation and management of the greenhouse climate based on greenhouse climatic data. The Penman–Monteith (P–M) equation model (Equation (1)), one of the most commonly used evapotranspiration models, was generated by combining the energy balance with the mass transfer theory (Equations (2) and (3)) [26].

$$\lambda ET = \frac{\Delta R_n}{\Delta + \gamma\left(1 + \frac{g_a}{g_c}\right)} + \frac{\rho C_p\, D_i\, g_a}{\Delta + \gamma\left(1 + \frac{g_a}{g_c}\right)} \quad (1)$$

$$\lambda ET = R_n - H_c \quad (2)$$

$$\lambda ET = \frac{\rho C_p}{\gamma}\; g_t\, D_c \quad (3)$$

where λ, latent heat of vaporisation (J kg^{-1}); ET, evapotranspiration rate (kg m^{-2} s^{-1}); Δ, slope of the saturation vapour pressure curve at temperature (kPa °C^{-1}); γ, psychrometric constant (kPa °C^{-1}); R_n, Net radiation intercepted by the crop (W m^{-2}); ρ, Air density (kg m^{-3}); C_p, Specific heat at constant pressure (J kg^{-1} °C^{-1}); Di, air vapour pressure deficit (kPa); g_c, crop stomatal conductances (m s^{-1}); g_a, crop aerodynamic conductance (m s^{-1}); g_t, total canopy conductance to water vapour transfer (m s^{-1}); H_C, is the sensible heat exchanged between the canopy and the air (W m^{-2}).

However, the accuracy of the P–M model pertains to variables that are not easily estimated such as the crop aerodynamic and stomatal conductances which are side and crop-specific. Recently, Nikolaou et al. [26], estimated cucumber resistances (resistance is the inverse of stomatal conductance) in different greenhouse climatic treatments (Table 2). The authors' reported for the first time on resistances calculation based on equations of canopy-to-air temperature ($T_c - T_a$) difference for an open field derived from the literature. The canopy and aerodynamic resistance were also parameterised based on a short time interval measurement (i.e., ten minutes basis) of leaf temperature and climatic variables using (Equation (4)), by rewriting the energy balance equation (Equation (2)) and combining Equations (5)–(7).

$$T_c - T_a = \frac{r_{ap}\, R_n}{p\, C_p} \times \frac{\gamma\left(1 + \frac{r_{cp}}{r_{ap}}\right)}{\Delta + \gamma\left(1 + \frac{r_{cp}}{r_{ap}}\right)} - \frac{VPD}{\Delta + \gamma\left(1 + \frac{r_{cp}}{r_{ap}}\right)} \quad (4)$$

$$H = \frac{\rho\, C_p\, (T_c - T_a)}{r_a} \quad (5)$$

$$\lambda ET = \frac{\rho\, C_p (e_s - e_a)}{[\gamma(r_a + r_c)]} \quad (6)$$

$$\gamma* = \gamma\left(1 + \frac{r_{cp}}{r_{ap}}\right) \quad (7)$$

where e_s, saturation vapor pressure at T_c (kPa); e_a, actual vapor pressure (kPa); ($e_s - e_a$), Saturation vapor pressure deficit (kPa); r_{cp}, is the canopy resistance (s m^{-1}); r_{ap}, is the aerodynamic resistance of a non-stressed crop (s m^{-1}), other equation parameters are the same as above.

As expected, aerodynamic and crop resistance values were affected by the greenhouse climate control equipment, cropping period and growth. To overcome the complexity of resistance calculations, several authors' [27–30] used the following simplified form of the P-M equation transpiration model, according to Baille et al. [31].

$$\lambda ET = A(1 - \exp(-KLAI))R_n + BLAIVPD \quad (8)$$

where LAI, leaf area index (m^2 leaf m^{-2} ground); A, value of equation parameters (dimensionless); B, value of equation parameters (W m^{-2} kPa^{-1}).

Table 2. Mean values of cucumber aerodynamic r_{ap} (s m^{-1}) and canopy resistances r_{cp} (s m^{-1}) were calculated in different growing periods and greenhouse climatic control systems.

Climatic Control Systems	**DAT 15–45**		**DAT 46–75**		**DAT 76–105**	
Spring Cropping Period 1	$\bar{r}_{ap}$	$\bar{r}_{cp}$	$\bar{r}_{ap}$	$\bar{r}_{cp}$	$\bar{r}_{ap}$	$\bar{r}_{cp}$
Forced ventilation	23	60	26	60	24	62
Wetted-evaporative pad combined with forced and natural ventilation	61	147	65	152	69	154
Autumn-winter cropping period 1						
Forced ventilation	64	82	63	75	50	85
Wetted-evaporative pad combined with forced and natural ventilation	86	120	83	125	78	172
Spring cropping period 2						
Forced ventilation and roof whitewash	35	127	45	152	42	133
Wetted-evaporative pad combined with forced and natural ventilation	25	92	48	167	54	179

However, even in the latter case, the simplified equation model must firstly be calibrated, as A and B equation coefficients respond differently under prevailing environmental conditions (Table 3).

Table 3. A (dimensionless) and B (Kg m^{-2} h^{-1} kPa^{-1}) values coefficient as estimated for different crops [32,33].

Crop	***A***	***B***	**Growing Conditions and Climatic Control Systems**
Tomato	0.58	0.025	Spain, autumn and spring growing period, growing media perlite bag, 7 plants m^{-2}
Cucumber	0.24–0.42	0.022–0.038	Spain, growing periods autumn 2 pl m^{-2} and spring 1.33 pl m^{-2}
	0.45	0.011	Cyprus, autumn-winter cropping period, growing media rock wool, greenhouse climatic treatment forced ventilation
	0.32	0.023	Cyprus autumn-winter cropping period, growing media rock wool, greenhouse climatic treatment wetted-evaporative pad combined with forced and natural ventilation
	0.15	0.040	Cyprus autumn-winter cropping period, growing media rock wool, greenhouse climatic treatment forced ventilation
	0.10	0.050	Cyprus autumn-winter cropping period, growing media rock wool, greenhouse climatic treatment wetted-evaporative pad combined with forced and natural ventilation

Considering that leaf temperature to be a very good indicator of a plant water status, a modification of the simplified P–M evapotranspiration model proposed by Nikolaou et al. [26] based on real-time leaf temperature sensors' feedback data. The proposed model (Equation (9)) does not use as inputs the data required for solar radiation or complex VPD calculations. The model validated within different environmental conditions and growth periods of a year than those calibrated with good results and therefore it could be used, in Mediterranean greenhouses, in a model-based irrigation decision support system:

$$\lambda ET = A(1 - \exp(-KLAI))(70.694T - 1376.69) + BLAI(0.192T - 3.156) \quad (9)$$

where T, leaf temperature (°C); other equation parameters are the same as above.

Several researchers attempted to evaluate the impact of water stress on different crops aiming at optimising water application, stimulate plant growth and/or production. For example, Nuruddin et al. [34] showed that the timing of the water stress in tomato plants was much more important rather than the magnitude of the stress. In another case, Hooshmand et al. [35], did not find any differences in crop formation prior to the fruiting stage, despite different irrigation applications. However, Schröder and Lieth [36] suggested that slight water stress between transplanting and flowering promote the first and second trusses of tomatoes. After the fruiting stage, partial root-zone drying in 85% of the water requirement significantly increased the water use efficiency (WUE) in a hydroponic tomato crop [37]. For soil-based greenhouse cucumber, deficit irrigation at 80% of crop evapotranspiration in certain crop stages positively affected crop water productivity (WP) [38].

Wang and Xing [39] evaluated the effects of different fertigation and irrigation regimes on a soil-based tomato concluding that WUE, yield and quality were more sensitive to changes in irrigation regimes than to changes in fertilisers. Furthermore, the most significant variable that has an influence on tomato productivity, in low and medium technology greenhouses in Spain, was the total irrigation water supply and the length of the growing cycle rather than the greenhouse technology [40]. Indeed, the frequency and the amount of irrigation varies with substrate water holding capacity and rooting volume. In rockwool slabs, where the rooting volume is very restricted, slabs may be watered five to six times per hour or up to 30 times per day under Mediterranean summer conditions. Harmanto et al. [41] have demonstrated that higher water savings of up to 25% could be obtained in a greenhouse drip irrigation system compared to outdoors tomatoes. In a soilless-based grown system increasing the irrigation interval (same daily amount applies) resulted in lower drainage emissions' outflow for a cucumber crop. In line, Rodriguez-Ortega et al. [18] also recommended a higher irrigation frequency with fewer amounts of water for the optimal irrigation management of tomatoes cultivated in a soilless perlite grown system. Open-drain soilless systems (Figure 1) may in addition reuse drainage in a second soil greenhouse or open field crop achieving a reduction in emissions to the water of up to 50% [42]. Whichever irrigation system is used inside the greenhouse it must meet the daily fluctuation of water needs. The use of data acquisition systems and modelling in high-tech greenhouses will increase the water and fertilisers supply. Table 4 shows WUE values of cucumber and tomato crops in different locations and growing conditions.

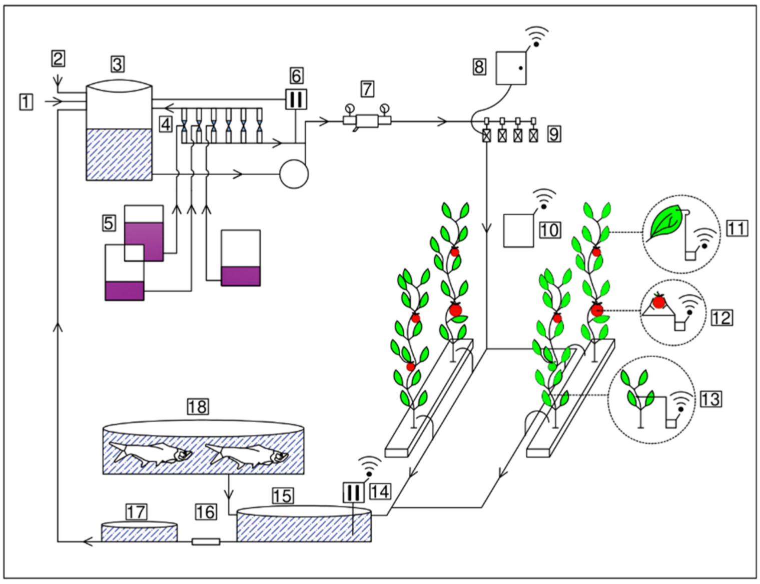

Figure 1. Irrigation and fertigation components in the closed soilless system; 1, irrigation water; 2, rainwater; 3–7, fertigation head components (3, mixing tank; 4, venturi system; 5, nutrients solution tanks; 6, pH and EC sensors; 7, filtration unit); 8, irrigation controller; 9, solenoid valves (i.e., electric on-off valve); 10, greenhouse climate control unit; 11–13, phyto-monitoring system (11, leaf temperature sensor; 12, fruit growth sensor; 13, Stem micro-variation sensor); 14, pH and EC sensors; 15, drainage collection tank; 16, disinfection system; 17, disinfected drainage tank; 18, aquaculture system (biofertiliser manufactured from fish waste/wastewater).

Table 4. Tomato and cucumber water use efficiency values (WUE; Kg m^{-3}) as cited by Nikolaou et al. [43].

Country	Cropping Conditions	WUE
	Tomato Crop	
France	Outdoor crop	14
	Greenhouse unheated	24
Italy	Greenhouse open substrate culture	23
	Greenhouse closed substrate culture	47
Spain	Greenhouse substrate culture	35
Israel	Outdoor crop	17
	Greenhouse unheated	33
Netherlands	Greenhouse open substrate culture	45
	Greenhouse closed substrate culture	66
Egypt	Outdoor crop	3
	Greenhouse unheated	17
	Greenhouse substrate culture	45
Cyprus	Outdoor crop	7
	Tunnel-grown	11
	Greenhouse soil culture	23
	Greenhouse substrate culture	30
Greece	Low tech greenhouse open substrate culture	20
	Low tech greenhouse, semi-closed substrate culture	28
	Low tech greenhouse, closed substrate culture	36
	High tech greenhouse, closed substrate culture	50
	High tech semi-closed greenhouse, closed substrate culture	80
	Cucumber Crop	
Cyprus	Outdoor crop	6.30
	Tunnel-grown	14.0
	Greenhouse soil culture	22.2
	Greenhouse with whitewash shading and a forced ventilation, open substrate culture, (spring crop)	34
	Greenhouse with wetted-evaporative pad combined forced and natural ventilation, open substrate culture, (spring crop)	38
	Greenhouse with heating and evaporative cooling, open substrate culture, (autumn-winter crop)	69
Italy	Solar greenhouse soil culture (fall-winter crop), irrigation setpoints based on soil water potential	22–45
	Solar greenhouse soil culture (spring-summer crop), irrigation setpoints based on soil water potential	59–103

3. Water Quality

Water quality is an important factor in irrigation management. The most common water quality-related problems are related to water salinity, specific ions toxicity and the infiltration rate, while other miscellaneous constraints include the corrosion of irrigation equipment [44]. Particularly, one of the most important aspects of low-quality saline water is the accumulation of salts in the rhizosphere and the restriction of plant growth, especially in arid and semi-arid regions worldwide. Soil salinity is estimated by electrical conductivity (EC) measurements, which corresponds to the osmotic potential outside the roots [45]. It is well known that salinity reduces plant growth and there are differences in tolerance to salinity among different species and between cultivars [46]. Table 5, presents the assessing permissible levels for tomato and cucumber crops' water and soil extract electrical conductivity (EC_w, water salinity; EC_e, soil extract salinity) without yield reduction and the percentage of yield reduction per unit increase in salinity based on Food and Agricultural Organization-FAO [44].

Table 5. Tomato and cucumber percentage of yield reduction as influences by irrigation water and soil (saturation extract) salinity (dS m^{-1}) increase.

Crop	100%		90%		75%		50%		0%	
	EC_w	EC_e	EC_w	EC_e	EC_w	EC_e	EC_w	EC_e	EC_w	EC_e
Tomato	1.7	2.5	2.3	3.5	3.4	5.0	5.0	7.6	8.4	13
Cucumber	1.7	2.5	2.2	3.3	2.9	4.4	4.2	6.3	6.8	10

From Table 5, one can be observed that EC_e is expected to be about 1.5 higher than the EC_w considering a 15–20% leaching fraction and a percentage of 40-30-20-10% of water use from the upper to the lower root zone. However, in greenhouses the salt concentrations in the soil many times increased in much higher values. It is common, after the end of the cropping period EC_e values of up to 15 to 18 dS m^{-1} (unpublished data, Cyprus Department of Agriculture). This is mainly because of the excess application of fertilisers, the minimum leaching, and the use of low irrigation water quality. Tomato and cucumber are classified as moderately sensitive crops, in relation to water salt content and the toxicity of specific ions. Cucumber is classified as moderately sensitive to boron concentration in the irrigation water (maximum concentration 2.0 mg L^{-1}) and tomato as a moderate tolerant with an upper threshold limit at 4.0 mg L^{-1}. Maximum permissible concentrations of chlorides for tomato and cucumber without yield losses estimated at 875 (mg L^{-1}) [44]. Local climatic and soil conditions should be taken into account when evaluating salinity and boron tolerance toxicity. For example, plants in gypsiferous soils may tolerance about 2 dS m^{-1} higher EC_e compared with soil containing a low $CaCO_3$ content indicated in Table 5. For instance, Phogat et al. [47] suggested that annual gypsum application at a rate of 1.7 t. ha^{-1} together with a leaching fraction of at least 20% was adequate for managing this soil salinity and sodicity hazard. The calculated soil salinity threshold values for yield decline were 1.73 dS m^{-1} for EC_e and 2.52 dSm^{-1} [48]. Controversially, in soilless tomato crops, water with electrical conductivity up to 4.0 dS m^{-1} positively affected photosynthetic rate, crop growth [49] and fruit taste quality characteristics. Recommended EC, Na and Cl upper limits for open drain systems been at 1.0 dS m^{-1}, 3.0 and 2.8–3.0 mmol L^{-1}. In semi-closed or closed systems, those values should be lower than 0.5 dS m^{-1}, 1.5 and 1.5 mmol L^{-1}.

4. Alternative Water Resources

Alternative water resources (i.e., desalination, captured condensate, brackish, seawater as a complementary irrigation source) have been tested in an attempt to develop new water resources for greenhouse horticulture. Treated wastewater (TWW) reuse may have a lower environmental impact than other alternative water supplies and may offer a range of economic, environmental and social benefits.

The main concern in using TWW arises from the potential pathogenic and toxic pollution of agricultural produce. However, major technological advances have been made with respect to producing safe treated wastewater TWW (i.e., membrane bioreactors, advanced oxidation processes, disinfection), while also several comprehensive guidelines and criteria have been set and implemented to ensure both environmental sustainability and public health from potential negative effects of TWW reuse [50,51]. All regulations and criteria proactively incorporate extensive risk management schemes for the production of TWW of specific quality required for a particular need. Therefore, high-quality TWW (tertiary treated and disinfected) is now considered suitable for the irrigation of all crops that are consumed raw, given that some specific requirements are satisfied (irrigation method).

Several studies have investigated the impacts of TWW reuse for the irrigation of several crops, including vegetables, on the uptake and bioaccumulation of potentially toxic elements in the edible parts of such plants, as well as on the microbial contamination of these tissues. Results revealed that high-quality tertiary treated effluent can be safely reused for the irrigation of vegetable crops either grown in an open field or under protected agriculture, including tomatoes [52–54], cucumber [55] and other vegetables [56–58].

The efficiency and advantages, as well as potential drawbacks, regarding the use of TWW for the fertigation and irrigation of tomato and cucumber plants under greenhouse conditions are closely related to the quality of TWW used; i.e., the source of sewage, the treatment process applied, the physicochemical properties and the microbial load of TWW used [10]. Bar-Tal et al. [59] reviewed the practices that simultaneously optimise the water and nutrient use efficiency in fertigation and irrigation with TWW under both open field and greenhouse cultivation, by presenting the Israeli experience (where TWW irrigation is a common practice), highlighting that the characteristics and composition of TWW are governing its potential use and benefits. Risks and challenges concerning TWW use are fouling of pipes and clogging of emitters and salinity development due to high salt concentrations in TWW compared with freshwater, whereas benefits concern the possible contribution of TWW components to availability of nutrients, especially N, P, K and micronutrients [59]. Recently, the effects of using municipal solid waste-derived compost as a soil amendment (5, 10, 20, 40%), fertigation and/or TWW irrigation on yield, plant physiology and fruit quality of tomato plants (*Solanum lycopersicum* L.) grown in pots under greenhouse conditions, were evaluated [60]. TWW irrigation supported the mineral status of the growing media, while also increasing the biomass ($\geq$20%) of plants, even though it did not affect the yield. Though, the combination of high compost ratios and TWW irrigation negatively affected stomatal conductance, leaf photosynthesis, chlorophyll fluorescence and internal CO_2 concentration. Fruit ascorbic acid, acidity, total soluble solids, firmness, and total phenolics were increased with TWW irrigation, but marketability did not. Also, lower levels of bacteria such as the Escherichia coli and total coliform were counted on fruit from TWW-irrigated plants compared with control, highlighting that TWW could be safely used for the irrigation of tomatoes in the greenhouse, following safety aspects [60]. Moreover, the effects of oxyfertigation (enrichment of the nutrient solution used with oxygen) of tomato crops grown on rockwool slabs and irrigated with TWW under Mediterranean greenhouse conditions, were assessed [61]. Results showed that TWW can be safely reused for the irrigation of tomatoes as such since oxyfertigation did not affect any of the irrigation and fertigation parameters evaluated, nor the aboveground biomass production rate and the quality and marketability of fruits. As far as cucumber cultivation is concerned, Pilatakis et al. [62] evaluated the impacts of direct application of primary and secondary TWW on plant growth and development in hydroponically grown cucumber. Both TWW sources applied resulted in increased yield, despite the fact that plant biomass, root length, leaf chlorophyll levels and total fruit number were not modulated among treatments. TWW irrigation resulted in disease spread in roots and fruits (by cross-contamination), thus further exploitation is necessary for microbial load reduction when TWW is applied.

Advances in analytical techniques over the last couple of decades revealed the presence of various contaminants of emerging concern (CEC) in TWW applied for irrigation, as the applied wastewater treatment technologies fail to completely remove such contaminants from the final treated effluent. CEC may include pharmaceuticals and personal care products (PPCPs), antibiotic-resistant bacteria (ARB) and resistance genes (ARGs), among others. The fate of these contaminants in the environment (i.e., soil, ground/surface waters, plants/crops) in the framework of TWW reuse applications is still under intensive investigation [22,63]. By exposing tomato plants grown in silica sand in pots under greenhouse conditions to three widely prescribed pharmaceuticals (10 μg L^{-1}) (diclofenac, DCF; sulfamethoxazole, SMX; trimethoprim, TMP) through the irrigation solution, Christou et al. [64] showed that plants can uptake and accumulate SMX and TMP in their fruits. Moreover, carbohydrate and soluble solids (total sugars, sucrose, glucose, fructose) content were significantly impacted by all studied pharmaceutical active compounds PhACs applied, while the plant productivity was unaffected.

Worth noting is the fact that the studied pharmaceuticals exerted, at least to some extent, significant impacts on the abundance of transcripts related to the biosynthesis and catabolism of sucrose. The extent of uptake of CEC by tomato and cucumber plants is largely dependent on environmental factors (i.e., soil environment, pH, organic matter content, clay content, climatic conditions such as temperature and humidity), plant physiology factors (i.e., the lipid content of roots) and plant species and genotype [64,65]. To this effect, Goldstein et al. [66] reported that the concentration of CECe in tomato fruit were much lower compared to that in the cucumber fruit exposed to CECe through the nutrient solution. This was attributed because the functions and physiological responses of cucumber fruits were similar to those of leaves (water transpiration, direct fixation of atmospheric CO_2) [67]. In addition, integrated modelling approaches have been lately developed aiming to predict the extent of pharmaceuticals' uptake by crop species, taking into account several factors governing CEC uptake, like soil properties, plant species and physiology, climatic conditions, etc. [68,69].

Another major challenge regarding TWW reuse in agriculture is that it may lead to the increase in the exposure of livestock and humans to ARB and ARGs, as ARGs can spread among soil and plant-associated bacteria, a fact that may have serious human health implications [70,71]. The uptake and bioaccumulation of antibiotics by TWW irrigated plants (or plants grown in soils amended with manure or biosolids) may lead to antibiotics-mediated selective pressure in plant endophytes. Importantly, the composition of the endophytic microbiome and its associated resistome appears to be linked to the corresponding soil microbiome and resistome [72]. The microbiome and its associated resistome of tomato plants grown in fields and irrigated with TWW or control water (in areas not affected by TWW irrigation or other major human activities) were recently examined. Results revealed that agricultural practices, such as soil amendment and fertilisation were the main drivers of ARGs loads on fruits, rather than TWW irrigation [73,74]. Therefore, whether or not TWW irrigation and fertigation represent a significant risk of exposure to ARBs, ARGs, and pathogens for the consumers is still a matter of discussion [71,75].

5. Fertigation Management

The application of fertilisers with the irrigation water (fertigation) is proposed as a means to increase efficient use of fertilisers and water, protect the environment, increase yield and sustain irrigated agriculture under intensive greenhouse production. The ferti(irri)gation water is prepared by adding the necessary amounts of fertilisers to the irrigation water via a fertiliser injector according to the target nutrient concentrations levels reported in various literature sources (e.g., [76]). Mediterranean greenhouse cultivation is dominated by vegetable production (mainly Solanaceae and Cucurbitaceae families i.e., tomato and cucumber crops), which generally relies on the high addition of fertilisers to render high yields [77]. To implement a sound fertigation strategy, both crop nutrient and water requirements should be considered throughout the growing season. In this respect, accurate crop evapotranspiration over the growing period must be determined under the prevailing microclimatic conditions of the region. The determination of actual crop water requirements is an indispensable component of the fertigation system and can be estimated through simulation models (e.g., FAO-56 Penman-Monteith equation) based on real-time measurements or periodically calculated based on climatic data of the region (e.g., FAO-24 pan evaporation method, [78]). Irrigation scheduling is reported elsewhere in this review article (see chapter 2) and will not be further discussed here.

5.1. Fertigation in Soil Cultivation

A good estimate to determine an efficient fertigation schedule is based on the quantities of nutrient uptake by the crop from the soil. Additionally, the difference between what the plant requires and what is supplied by the soil and water taking into consideration the fertiliser-nutrients uptake efficiency can be used to optimise soil fertility level. Unfortunately, nutrient uptake patterns vary by stage of growth and a number of factors such as climatic conditions, cultural practices, crop cultivars and losses account eventually for adjustments in the fertigation program. Thus, the use of fertigation recipes given in the literature (e.g., 150–180 ppm N, 30–50 ppm P and 200–250 ppm K) is not compatible with efficient fertigation management, as for the same crop, for each field, different fertigation schemes could be recommended. Therefore we will concentrate on the main principles of nutrition in fertigation. Nutrients absorbed by the crop are used for plant vegetative growth and reproductive development. Therefore, enough nutrients in the soil solution and the correct proportions are needed to satisfy the requirements for crop production and to satisfy the requirements of the non-harvested portion, which may include also an amount to build up soil fertility. This should not be ruled out in greenhouse cropping systems in which the aerial part of most crops is rather removed than incorporated in the soil. However, not all of the nutrients should necessarily come from fertiliser because part of them could be supplied by the supplying capacity of the soil. Thus, the amount of nutrients, which may be available to the crop from the soil should be estimated. This amount is then subtracted from the overall amount, which should be supplied by fertilisers. Generally, fruiting crops such as tomato, and cucumber require relatively little nutrition until flowering, when nutrient uptake accelerates, peaking during the fruiting cycle [76]. In general, nutrient uptake follow the same course as the rate of crop biomass accumulation characterised by initial exponential growth rate followed by linear growth. The N, P, K uptake rates and dry weight accumulation curves are illustrated in Figure 2 [79].

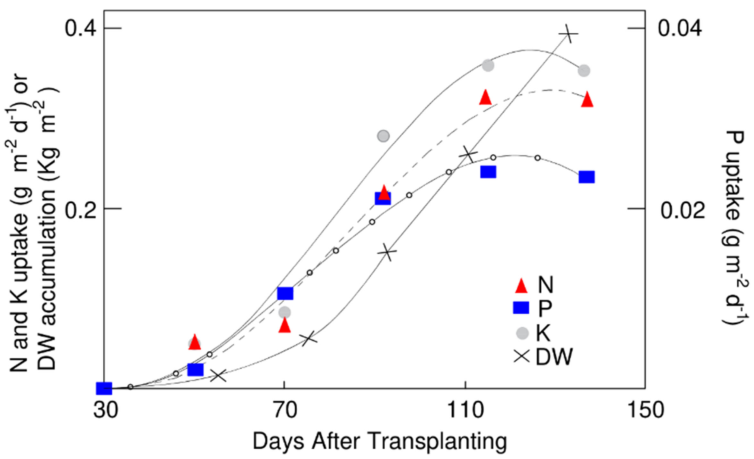

Figure 2. N, P, K uptake rates and dry weight (DW) accumulation as a function of time (DAT—days after transplanting) in topped tomato plants (adapted from Silber and Bar-Tal [79]).

The amounts of nitrogen (N), phosphorus (P) and potassium (K) removed in the harvested portion from the soil by Mediterranean tomato and cucumber crops for certain yield are given in the following Table 6; and Table 7 showed the N, P, K amounts required for canopy formation (leaves and roots) and amounts per additional ton of fruit produce. The adoption of known N, P, K uptake data to different growing conditions from those specified should be implemented carefully in specific fertilisation recommendations.

Table 6. Estimation of nutrients (N, P, K; kg ha^{-1}) removed in the harvested portion of tomato and cucumber crops for certain yield (t ha^{-1}) and total crop water needs (TW; m^3 ha^{-1}) under Mediterranean conditions.

Crop	N	P	K	Yield	TW
Cucumber, Open field	51	11	65	30	4760
Greenhouse	221	45	281	130	5780
Low tunnel	68	14	86	40	2900
Tomato, Open field	63	14	140	45	6540
Greenhouse	252	54	564	180	7430
Low tunnel	70	15	157	50	4620

Table 7. Nutrients required by selected crops for canopy formation (kg ha^{-1}) and fruit production (kg t^{-1}). (adapted from Papadopoulos [80]).

Crop	Canopy			Fruit		
	N	P	K	N	P	K
Tomato	95	12	108	1.80	0.17	3.13
Cucumber	60	8	66	1.40	0.35	2.16

In standard crop fertilisation schemes in greenhouse production nitrogen (N), phosphorus (P) and potassium (K) are the main elements in plant nutrition given the high N and K requirements of plants and that sufficient availability of P in soil is crucial for high yields in greenhouses. As a rule of thumb, N, P and K are constantly supplied via the irrigation water in greenhouse crops. Daily applications of these nutrients with fertigation systems increased the yield and quality of tomatoes and cucumbers increasing in parallel the nutrient uptake efficiency of these nutrients as reported repeatedly in the literature (e.g., [81–84]). On the other hand, the rest of the nutrients (essential for plant growth) are considered to be available in the water and soil and are not included in fertigation schemes [85]. Following this approach, Mg and trace elements are applied if indicated by soil analysis and Ca is supplemented only in acidic or saline soil conditions. Indicatively, average masses of micronutrients removed from the soil by vegetable crops per ton of fresh biomass production are 20 g Fe, 10 g Mn, 5 g Zn, 1 g Cu, 5 g B and 0.2 g Mo.

Based on the above information the following formula is used to estimate the overall amount of nutrients needed to be supplied by fertilisers for a certain yield [82]:

$$NF = (NR - SC + SM)100/UE \quad (10)$$

where *NR*: the nutrient requirement of the crop for certain yield (kg ha^{-1}), *SC*: the supply capacity of the soil (kg ha^{-1}), *SM*: the safety margin (kg ha^{-1}), *UE*: the fraction of nutrient uptake efficiency.

For micro-irrigation (i.e., systems with drip irrigation and microsprinklers) systems N, P and K uptake efficiency ranges (depending on soil type; higher on clayey soils and limited on sandy soils) between 0.75–0.85, 0.25–0.35 and 0.80–0.90, respectively. The amount of nutrients in the soil (kg ha^{-1}) that can be used by the crop is estimated from soil mass (t ha^{-1}) multiplied by the available nutrient value (kg t^{-1}) as determined by soil chemical analysis. Soil mass (t) derives from the multiplication of (i) area of plantation (m^2) the depth of the active rooting system (m), (ii) the fraction of total soil volume occupied by roots (in drip-irrigated tomato and cucumber crops this fraction is usually 30–50% of total soil volume) and (iii) soil bulk density (t/m^3). Finally, for intensive irrigated agriculture as safety amounts of P and K in soil could be considered the values of 15 and 60 ppm (g/t), respectively, and subsequently using soil mass to convert these concentrations into kg ha^{-1}.

Eventually, the nutrient concentration in the irrigation water (ppm) derives as the ratio calculated between the mass of nutrient (g) and the respective amount of irrigation water (tons) to be applied for the same period (continuous fertigation). On the other hand, to provide specific quantities of each nutrient to the crop in certain growth stages and not continuously, the following formula is used:

$$L = (NF \times E \times 100)/AN \quad (11)$$

where L, amount of fertiliser (kg ha^{-1}); NF, amount of nutrient (kg ha^{-1}); E, area of cultivation (ha); A, number of fertigation events; N, nutrient content of fertiliser (%).

Throughout the growing season, the fertiliser supply rate may be adjusted based on soil and plant nutrient status (i.e., corrective approach). Desired levels of exchangeable soil nutrients are reported [85] as follows (mg/kg dried soil): P (10–40), K (120–500), Ca (1200–5000), Mg (60–350), Fe (5–150), Mn (2–80), Cu (0.5–2), Zn (0.7–2) and B (0.3–1.5). With regard to soil N, soil minerals do not contain N, and 90% of soil N is associated with soil organic matter. About 1–3% of soil organic matter is mineralised each year and this corresponds to approximately 144 kg of N/ha from which, crops may use about 50 percent (Gobin et al., 2011). Afterwards, to assess the impact of fertilisation, leaf tissues analyses are made. For tomato and cucumber, the optimum (sufficiency) range of nutrients in leaf tissues most used is presented in Table 8.

Table 8. Nutrient concentrations sufficiency range of macronutrients (%) and micronutrients (ppm) on a dry basis in young fully expanded leaves of tomato and cucumber crops [86,87].

Macronutrients	Tomato	Cucumber	Micronutrients	Tomato	Cucumber
N	3.5–5.0	3.5–5.5	Fe	80–200	80–200
P	0.35–0.75	0.35–0.8	Zn	30–100	40–100
K	3.5–6.5	3.0–5.0	Mn	100–300	100–300
Ca	2.0–4.0	2.0–10	Cu	7–20	7–17
Mg	0.35–0.8	0.4–0.8	B	30–80	30–80
			Mo	>0.4	1.0–2.0

For dynamic corrections in fertigation schemes based on leaf tissue analyses, the following formula is used according to Koukoulakis and Papadopoulos, 2003:

$$NF_{corr} = [0.8 \times TC_{max} + 0.2 \times TC_{min} - NTC] \times NF/[TC_{max} - NTC] \quad (12)$$

where NF_{corr}, corrected amount of selected nutrient (kg ha^{-1}); NF, the calculated amount of selected nutrient using Equation (10) (kg ha^{-1}); TC_{max}, maximum optimum leaf tissue concentration of the selected nutrient (% or ppm); TC_{min}, minimum optimum leaf tissue concentration of the selected nutrient (% or ppm); NTC, measured leaf tissue concentration of the selected nutrient (% or ppm).

Furthermore, over the last decades, crop modelling has been considered an excellent tool for efficient fertilisation management. For example, modelling plant nutrition can be accomplished through simplified models based on the concept of nutrient uptake concentration (mass of nutrient per volume of water absorbed). Based on these parameters the nutrient requirements of tomato and cucumber and other vegetable crops have been estimated and presented by Sonneveld and Voogt [77]. Generally, adding amounts of water and nutrients according to the expected mean uptake concentrations and controlling nutrients level in the root zone solution and within plants constitutes a sound fertigation strategy. Additionally, more complex simulation models can be effective in decision support systems (DSS). Incrocci et al. [76] list in review works, the main DSS for fertigation management such as GesCoN, VegSyst, Fertirrigere and EU-Rotate_N used in tomato and cucumber crops.

5.2. Fertigation in Soilless Systems

Today, tomato and cucumber are the most important vegetable crops cultivated in soilless culture in Europe and Worldwide [88,89]. The differences in fertilisation management between soil-grown crops and soilless culture (i.e., growing plants without the use of soil) arise mainly from the fact that plants in soilless culture roots grow in a restricted volume of substrate, which imposes limited nutrient reserves. Thus, fertilisation in soilless culture focuses on all essential macro- and micronutrients. Particularly, fertigation head units (Figure 3) add pre-mixed or individual-salt fertiliser material in the primary water to form the outgoing irrigation solution, termed 'nutrient solution (NS)' (Savvas and Neocleous, 2019). However, NS composition needs to be fine-tuned to meet the special nutritional needs of the crop cultivar following the developmental stage and the prevailing climatic conditions. Thus, several authors have recommended NS compositions and methods of calculations for different growing conditions (e.g., [77,90–92]). In particular, calculations needed to prepare a NS satisfying particular nutrient requirements of the crop can be overcome by the use of specific algorithms (Savvas and Adamidis, 1999; Sonneveld, 2002), which may be incorporated in modern computational tools operating online as decision support systems (e.g., https://nutrisense.online/, accessed on 20 August 2021 [93]).

The following tables give the recommended NS compositions for greenhouse tomato and cucumber crops grown in north-European countries (Table 9, [77,90]) and in the Mediterranean basin (Table 10, [92,94]). Technologies of nutrient recycling (closed soilless systems) are already applied in northern European greenhouses, however, in the Mediterranean greenhouses are rarely applied as in most cases about 30–35% of the NS supplied to soilless cultivations drains out of the root zone (open soilless systems).

Table 9. Nutrient solution (NS) composition supplied to soilless tomato and cucumber crops, in open and closed soilless systems under northern European climatic conditions.

Desired Nutrient Solution Composition	Tomato		Cucumber	
	A *	B	A	B
EC dS/m	2.60	1.6	2.2	1.7
pH opt,	5.6	5.6	5.6	5.6
[K] mmol/L	9.5	6.5	8.0	6.5
[Ca]	5.4	2.75	4.0	2.75
[Mg]	2.4	1.0	1.375	1.0
[NH_4]	1.2	1.0	1.25	1.0
[NO_3]	16.0	10.75	16.0	11.75
[SO_4]	4.4	1.5	1.375	1.0
[H_2PO_4]	1.5	1.25	1.25	1.25
[Fe] µmol/l	15	15	15	15
[Mn]	10	10	10	10
[Zn]	5	4	5	5
[Cu]	0.75	0.75	0.75	0.75
[B]	30	20	25	25
[Mo]	0.5	0.5	0.5	0.5

* A = Open soilless system, B = Closed soilless system.

Table 10. Nutrient solution (NS) composition supplied to soilless tomato and cucumber crops, according to the developmental stage under Mediterranean climatic conditions.

Desired Nutrient Solution Composition	Tomato Stages					Cucumber Stages		
	I.	II.	III.	IV.	V.	I.	II.	III.
EC (dS/m)	2.80	2.50	2.40	2.40	2.30	2.40	2.20	2.10
pH	5.6	5.6	5.6	5.6	5.6	5.60	5.60	5.60
[K]	6.80	7.00	7.50	8.00	7.50	5.70	5.60	6.30
[Ca]	6.40	5.10	4.70	4.50	4.40	4.20	3.50	3.00
[Mg]	3.00	2.40	2.20	2.10	2.00	3.00	2.50	2.30

Table 10. *Cont.*

Desired Nutrient Solution Composition	Tomato Stages					Cucumber Stages		
	I.	II.	III.	IV.	V.	I.	II.	III.
[NH4]	0.80	1.50	1.20	1.20	1.20	1.00	1.50	1.30
[NO3]	15.5	14.30	12.30	12.40	12.30	15.50	14.20	13.50
[SO4]	4.50	3.60	4.10	4.00	3.60	2.00	1.60	1.50
[H2PO4]	1.40	1.50	1.30	1.50	1.50	1.10	1.20	1.20
[Fe]	20	15	15	15	15	20	15	15
[Mn]	12	10	10	10	10	12	10	10
[Zn]	6	5	5	5	4	6	5	5
[Cu]	0.8	0.8	0.8	0.7	0.7	0.8	0.8	0.8
[B]	40	35	30	30	25	50	40	35
[Mo]	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5

I: starting nutrient solution; Tomato II–V. flowering clusters 1–3, 3–5, 5–10, >10; Cucumber II and III: vegetative and reproductive stages, respectively.

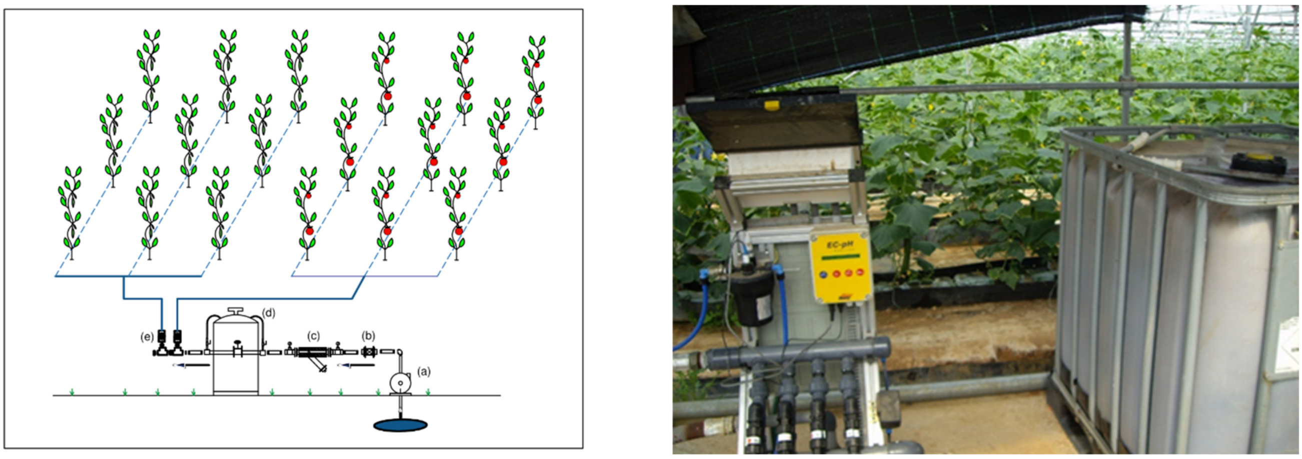

Figure 3. Groundwater supply pump (**a**) and an irrigation control head unit (left-hand side; **b** to **d**) consisted of a water meter (**b**); a filter (**c**); a fertiliser injector unit (**d**); electric valves (**e**), and a fertigation head used for soilless cucumber production in Mediterranean greenhouses (right-hand side).

6. Conclusions

The semi-arid Mediterranean region has been classified as a global climate change hot spot, already witnessing the impacts of climate change, including a significant decrease in precipitation and an increase in mean air temperatures values. The overexploitation of groundwater resources has resulted in the lowering of water level, seawater intrusion and groundwater quality deterioration. In fact, crop yield is significantly affected by the quality of groundwater, therefore, it has been of great economic and environmental concern. The scarcity of water greatly affects the sustainability of irrigated agricultural crops. Rural areas are expected to experience major impacts of climate change on water availability and supply, infrastructure and agricultural incomes, reduced agricultural production and increase food insecurity with socio-economic consequences, such as increasing poverty and migration.

Recognising the critical role of water, this review article draws attention to the challenges that greenhouse growers in arid and semi-arid areas in the Mediterranean facing related to water and nutrient supply for tomato and cucumber crops. Indeed, for several countries within the EU (such as Spain, Italy, Greece), the water policy has been driven to a large extend by the EU legislation, which provides the framework for comprehensively addressing water protection and for achieving good status for inland surface waters, coastal waters and groundwater. Various management plans were developed and adopted to strengthen aquatic ecosystems and promote the resilience of the environment to climate change, therefore manage inputs (i.e., water and fertilisers) in a more acceptable manner.

More recently, in many cases, technological improvements in irrigation and water-saving practices have been adopted by growers. However, the adoption is relatively low because growers do not benefit directly from water-saving and these systems are of high cost. The lack of a precise internal control of the climate in protected cropping systems and the insufficient water and nutrients supply, increased biotic and abiotic stresses and negatively affected yield. As a consequence, water and nutrients are depleted and potentially lead to groundwater contamination. For this reason, factors controlling the crop water uptake should be properly considered for proper irrigation scheduling as discussed in this paper. However, farmers' education and training under local conditions are one of the crucial pre-conditions for the sustainable implementation of many of these options.

This review article is a timely contribution as it cuts across the water and fertiliser sectors and summarises the highest level of knowledge on water and fertilisers management in relation to variations in environmental conditions and the challenges we face that can help in sustainably strengthening food security.

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