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WATER USE EFFICIENCY IN GREENHOUSE SYSTEMS AND ITS APPLICATION IN HORTICULTURE

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Abstract

Traditional culture system (TCS) in open field is high demanding in water and other natural resources and thus has driven the development of protected cultivation systems with innovative horticultural growing techniques. Greenhouse systems and soilless culture system (SCS) can allow obtaining high yields and improving water use efficiency especially in marginal and arid regions. Desert areas have tapped the opportunity arising from technical innovation to create new chances for horticulture development with important social and environmental impacts; today these advanced techniques can be successfully adopted in every context in which a high-water use efficiency is needed. Indoor and vertical farming represent new possible cultivation strategies for urban and peri-urban areas where the SCS plays an important role. Integrated systems must be adopted for lowering the production costs such as the use of innovative lighting systems and ICT controlling units for real time management. In fact, the application of highly specialized growing techniques represents an efficient tool to increase sustainable agricultural productions, thanks to the interaction between growers, supply chain partners, research institutes and governmental agencies.

Key words*: case studies, hydroponics, innovative production systems, soilless culture systems, WUE.*

INTRODUCTION

The industrialization of agriculture led to increase homogeneity across food systems as farming techniques and markets become more standardized (Lyson, 2004; Lyson and Guptill, 2004). Therefore, the complex social relationships underlying agriculture and ecosystem service provision have become less visible. The main objectives of the agricultural systems are competitiveness, efficiency and environmental protection through innovative practices and environmentally friendly technologies (Lundqvist et al., 2008; Nellemann et al., 2009; FAO, 2013). The request of high-quality horticultural products is increasing, due to the growing interest of consumers in fresh products of high organoleptic, nutritional, and functional value. The quality of fresh horticultural commodities has been described as "*a dynamic composite of their physicochemical properties and evolving consumer perception, which embraces organoleptic, nutritional and bioactive components*". The increase of input costs and the stabilisation of sale prices of produce have driven greater investments in technology, crop yield (which is increased more than two-fold from 1975) and resource efficiency, creating a dynamic system: the intensive horticulture (Galdeano-Gómez et al., 2013). The effect of new cultivars and more efficient production system management are detectible in terms of increased production and productivity in protected cultivation. The protected cultivation systems allow a reduction of the transpiration, respect to open field in which circa the 98% of the water taken up by an annual plant is lost (FAO, 2004) (Figure 1).

Water is fast becoming a scarce resource in many areas of the world (FAO, 2016) and its management is one of the most important political, social, and economic issues of the twenty-first century (Abou Hadid, 2013). The United Nations World Water Development Report (2018) stated that nearly 6 billion peoples will suffer from water scarcity by 2050 as a result of increasing demand for water

(Boretti and Rosa, 2019). Agriculture is the largest water user worldwide, accounting for 70% of total freshwater withdrawals on average, but these amounts can reach as much as 95% in some developing countries. Agriculture activity, if not well managed, can be a major source of water pollution from excessive nutrients supply, pesticides, and other contaminants, which if unmanaged can lead to significant social, economic, and environmental costs (FAO, 2016). Low irrigation efficiency can be primarily attributed to water mismanagement, technical distribution problems and poor maintenance of irrigation structures (Abou Hadid, 2013). The low water availability is forcing many growers to use water with relatively high salt concentration for crop irrigation or to improve methods, techniques, and management practices in agricultural and horticultural production. It is estimated that 18% of cropland is irrigated accounting for ca 40% of productivity with an irrigation efficiency of 40-65% for furrow irrigation, 45-75% for basin irrigation, 60-70% for sprinkler irrigation, 80% for localized irrigation (Abou Hadid, 2013). Furthermore, more strict environmental regulations related to water use are now prevailing in many countries.

Figure 1. Cultivation in areas with water scarcity

Awareness of the pollution, associated with intensive agriculture, forces greenhouse growers to adopt environment-friendly cultivation methods, such as closed soilless culture (Vox et al., 2010; Gruda, 2009) (Figure 2). Soilless culture system (SCS) is a cropping system that gained popularity worldwide in the 1930s in plant nutrition experiments (Engindeniz, 2004). The nutrient solution (NS) supplied to the growing system can be collected and reused (closed-loop system) or lost as drainage (open-loop system).

Figure 2. Soilless cultivation in open field and protected cultivation in areas with water scarcity

Closed SCSs are environmentally friendly, reducing the amount of the water and nutrients used for each growing cycle. However, the management costs are higher and require skilled agronomists for controlling the NS composition and properties during recirculation. Open SCSs are easier in the management, with a NS freshly prepared and delivered to the crops. The disadvantages of these systems are related to the higher amount of water and nutrients used. SCS consents to produce raw vegetables by using NS with or without solid inert material (e.g. rockwool, turf stone, clay granules, sawdust, flexible polyurethane foaming blocks, composed hardwood bark, peat) as support to the roots (Engindeniz, 2004). Inert substrates are also suitable to significantly reduce the evapotranspiration that is of particular interest in areas with adverse growing conditions (Gruda, 2009). Currently, about 3.5% of the worldwide area cultivated under tunnels and greenhouses for vegetables production adopts the soilless agriculture techniques based on hydroponic solution, such as floating systems, nutrient film technique or aeroponics, (Sambo et al., 2019). This significant diffusion at the field scale undoubtedly highlights the presence of many advantages such as plant protection prevention, product quality improvement, improving water use efficiency (WUE), and ensuring high yields (Kinoshita et al., 2016; Ferrante et al., 2003; Nicola & Fontana, 2007; Fontana & Nicola, 2009; Nicola et al., 2016).

In SCS, the NS composition has to be adapted to the quality of water, the crop species, the growth stage, and the climatic conditions. Only the use of modern information and computer technologies can permit to pursue these objectives. Suitable automation technologies are frequently based on real-time measurement of parameters connected either to the greenhouse microclimate (e.g., solar radiation, vapor pressure deficit, air temperature) or to the growing media (GM) water status (water tension or content). SCS is highly productive, allowing controlling and managing efficiently the input usage precision, increasing the yield-related WUE, reducing waste (e.g. of N supply). It is suitable for producing vegetables with both a short culture cycle and a high planting density, increasing earliness and allowing the extension of the growing seasons (Fontana & Nicola, 2008; Rodríguez-Hidalgo et al., 2010; Grewal et al., 2011; Scuderi et al., 2011). SCS is also able to recycle water and nutrients because the drainage can be recovered; the reuse does not in general restrict crop yields while reducing the water source pollution (Grewal et al., 2011). In the past, SCS was used in open systems, thus the surplus of supplied water and of nutrients were lost reducing the efficiency, increasing waste and resulting in contamination of groundwater, particularly with nitrates and phosphates (Incrocci et al., 2006; Savvas et al., 2007). SCS is useful and suitable to apply positive stress to plants. Indeed, application of eustress (positive stress), such as salinity or nutritional stress, can elicit physiological responses and molecular mechanisms that cause the accumulation of bioactive compounds such as non-structural carbohydrates and health-promoting phytochemicals such as lycopene, β-carotene, vitamin C, and the overall phenolic content of tomato fruits (Rouphael and Kyriacou, 2018). In addition, salinity eustress can decrease the accumulation of anti-nutrient compounds such as nitrate, thanks to the antagonism in absorption between chloride and nitrate (Rodriguez-Ortega et al., 2017; Rouphael and Kyriacou, 2018). In Europe, the legislation drafted to reduce the environmental impact of horticulture stemming from fertilization runoff, is forcing greenhouse growers to invest in closed systems (Savvas et al., 2007). In addition, SCS can improve raw material quality at harvest avoiding over-head irrigations and the contact between NS and edible parts reducing microbial contamination, eliminating soil and chemical residue spoilage and can solve problems caused by soil-borne diseases (Fontana & Nicola, 2009). FAO (2004) reported that 1 m^3 of water consumption affects yield according to the cropping system used, ranging from 3 kg of tomato production obtained in open field system, to 10-12 kg in protected cultivation system to 30 kg in SCS in protected cultivation system. The water consumption to produce 1 kg of commercial yield of vegetables varies considerably from TCS in open field to SCS in greenhouse (tomato 123 L vs 13 L; cucumber 205 L vs 10 L; lettuce 96 L vs 5 L, respectively) (FAO, 2004). Jovicich et al. (2007) reported that greenhouse cucumber crops in Florida (USA) required 33% less of the water amount, 28% less nitrogen and 23% less potassium per kg of fruit compared with a field grown cucumber crop. Among the different SCSs, floating systems (FS) are relatively cheap and easy-to-use sub-irrigation systems that can be implemented either with a continuous flotation (FL) or with an ebb-and-flow flotation (EF) (Fontana & Nicola, 2009). FL consists of trays floating continuously on a water-bed or NS and requires relatively little maintenance or labour cost, resulting in a more efficient use of water and greenhouse space (Fontana & Nicola, 2008). EF is scheduled with drying (ebb) periods with discontinuous flotation or aerating the NS to reduce plant hypoxia for those vegetables as rocket which may suffer stress due to the consumption of oxygen dissolved in the NS if grown in FL (Son et al., 2006; Nicola et al., 2007; Fontana & Nicola, 2009). The EF system may allow 85% reduction of water use, 50% of fertilizer use, 50 to 60% of pesticide use, elimination of groundwater contamination and rare occurrence of foliar and soil-borne diseases (Son et al., 2006; Fontana & Nicola, 2009). With the nutrient film technique (NFT), a continuous or intermittent flow of NS pumped from a tank flows over the roots in a tube or tray and then returns to the tank assuring adequate aeration of the roots

(Cooper, 1979). Recycled NS must be monitored and checked regularly to adjust nutrient strength, conductivity, pH, and control the supply because if the pump stops working, plant roots are prone to drying out (Cooper, 1979; Wolosin, 2008). Cropland currently occupies about 1.53 billion hectares or 12% of the Earth's ice-free land and the most suitable area for cropping have already been converted to cropland (Kummu et al., 2012). Expansion is therefore often into marginal areas where crops productions are particularly exposed to extreme conditions and stress reducing productivity and adaptation (West et al., 2010; Kummu et al., 2012). Thus, beside to be widely used in developed countries, greenhouses and SCSs have been introduced in marginal areas or in arid lands where favourable climate conditions but problematic soil properties, water scarcity or erratic rainfall distribution exist (Massa et al., 2011; Gruda, 2009). Some authors have shown the importance of the different environmental conditions in the design of controlled structures and strategies, for which knowledge of the characteristics of each region is essential (Mazuela et al., 2012).

CASE STUDIES

1. Arid Regions

1.1. The Almería phenomenon

The Almería region is characterized by an intensive horticultural cropping system. Almería underwent an unprecedented transformation in Spain's recent economic history, thanks to the agricultural development (Aznar-Sánchez et al., 2011; Garcia-Caparros et al., 2017). This represents an example of how large-scale greenhouse agriculture can affect, both positively and negatively, the landscape (Aznar-Sánchez et al., 2011; Giagnocavo, 2012).

Almería is located in the autonomous community of Andalucía in the South East of Spain (Figure 3). The area is characterized by an extremely arid climate, with average temperature of 17-20°C, due to the proximity of the mountains which provide a protective boundary against cold northerly winds and winter storms (Tout, 1990), little temperature variations between day and night, about 3000 hours of annual sunshine and about 200-250 mm of rain per year (Cantón et al., 2003; Downward & Taylor, 2007; Aznar-Sánchez & Galdeano-Gómez, 2011).

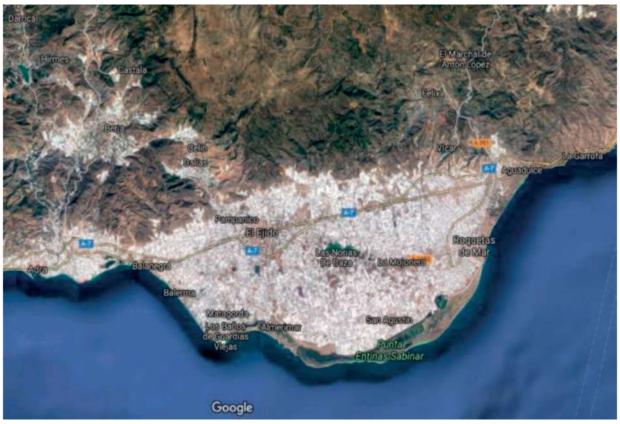

Figure 3. The area of the Almería region with the intensive protected cultivation development (source: maps.google.com)

Because of the location, climate and lack of water, Almería has not being rapidly urbanized (Cantliffe & Vansickle, 2012) and until the end of the 1960s social and economic indicators characterized Almería as an underdeveloped and in a stage of decline province (Aznar-Sánchez et al., 2011). Environmental factors have played an important role in the province change, which led to the adoption of a production system more efficient, especially in the use of water, and more sustainable (Galdeano-Gómez et al., 2008; 2013). In the 1950s, agricultural production was mainly based on table grapes cultivation (produced on wire trellis systems covered with plastic to induce earliness) and citrus (Cantliffe & Vansickle, 2012). With modern transportation and the accessibility to other varieties, the table grape industry suffered a decline becoming an unproductive source of cropping for farmers, encouraging them to look for new sources of income (Wolosin, 2008). In that period the sand-plot (*enarenado*) technique was introduced (Figure 4). It consists in the preparation of a mechanically levelled soil surface, covered with a layer of compacted clay, fermented manure and sand or coarse grit (Tout, 1990). The National Institute for Colonization promoted the use of the technology necessary for extracting the abundant underground water resources compensating low and erratic rainfall, provided infrastructure for water and electricity use and encouraged people to settle in the area offering technical and financial advice (Giagnocavo et al., 2010; Aznar-Sánchez & Galdeano-Gómez, 2011; Giagnocavo, 2012). Consequently, farmers from the close rural areas were attracted by the proposition of easy access to land, the possibility of obtaining their own property and the great profitability (Baldock et al., 2010; Aznar-Sánchez et al., 2011). The new farms were supported by the adoption of several technological innovations developed and rapidly incorporated in the fields, including windbreaks to protect the sand-plots system from high winds and to prevent sand loss (Aznar-Sánchez et al., 2011).

Figure 4. Typical crop in *enarenado* system in Almería area

During the 1970s and 1980s, several grape cultivations were converted to vegetable fields because of the greater profitability and to the introduction of greenhouse and new farming techniques (Cantliffe & Vansickle, 2012). These innovations completely transformed the unproductive lands into prosperous farms, providing effective protection against weather and environmental conditions contributing to increase yields and precocity, allowing the extension of the growing season, the quality and water conservation (Ferraro García & Aznar-Sánchez, 2008; Aznar-Sánchez & Galdeano-Gómez, 2011). In 1975, approximately a quarter of the irrigated area of Almería was covered by greenhouses (Wolosin, 2008). The general horticultural market expansion and the increasing demand for off-season produce were the main reasons for the continued investment and farm development. Furthermore, this expansion was supported by several initiatives which were introduced for family-run farms and cooperative bank, including private financing structures and credit facilities offered by marketing farms (Aznar-Sánchez et al., 2011; Giagnocavo, 2012; Galdeano-Gómez et al., 2013).

In the 1980s the attention to the efficient use of irrigation water is grown and in 1984 the Government of Andalucía reduced the expansion of irrigated greenhouses with legal restrictions due to the over-exploitation of the water resources available (Wolosin, 2008). In the following years, the Government of Andalucía funded the construction of deeper wells, water supply lines and new irrigation pipes in response to water shortages and farmers' demand (Wolosin, 2008). Drip irrigation was mandatory applied to reduce water use and evapotranspiration loss, while increasing the efficiency of its distribution on the plants (Tout, 1990; Cantliffe & Vansickle, 2012). More precisely, in recent years, the fertigation is mostly adopted as agro-technique, providing a very good opportunity to minimize water and nutrients losses simultaneously (Garcia-Caparros et al., 2017; Incrocci et al., 2017). As a consequence, to the limitations in the use of water resources, Almería experienced little to no greenhouse construction from 1985 to 1989 (Wolosin, 2008). The Almería's agriculture consolidation took place in the 1990s with constant improvement in production technique, technological innovation, and marketing for the competitiveness maintenance (Aznar-Sánchez et al., 2011). Today, almost 90% of the greenhouse area in Almería produces soilless vegetables, which are grown on an artificial soil made by clay, sand, gravel, manure and either perlite or rockwool as soilless media, and the production has increased optimizing costs (Cantliffe & Vansickle, 2012; Giagnocavo, 2012). The land area dedicated to horticultural greenhouse farming has increased dramatically from approximately 3,000 ha in 1975 to more than 30,000 ha at present (Aznar-Sánchez et al., 2011; Garcia-Caparros et al., 2017; Parra et al., 2019). Nowadays, in Almería there are 36,000-

40,000 ha of greenhouse vegetable crops representing more than half of the total area of greenhouses in Spain dedicated to vegetables and the most concentrated greenhouse area in Europe. Particularly, the major greenhouse area is concentrated in the South-West of the province, at Campo de Dalías, with a concentration of over 16,000 ha of greenhouses making it one of the most important areas of intensive farming worldwide (Aznar-Sánchez & Galdeano-Gómez, 2011; Aznar-Sánchez et al., 2011). In Almería, the volume greenhouse production increased from 600,000 metric tons to 2.7 million metric tons in the last 30 years, representing about 25% of the national total production, making Almería the top vegetable growing province in Spain (Wolosin, 2008; Cantliffe & Vansickle, 2012). The grown interest in Almería production from national and international produce companies has brought additional changes to the greenhouse system and the expansion of auxiliary industries related to construction, maintenance, as well as to the distribution, packaging, seeding, recycling of produce and research centres (Aznar-Sánchez & Galdeano-Gómez, 2011; Aznar-Sánchez et al., 2011; Cantliffe & Vansickle, 2012). Almería vegetable production includes 30 different crop species, representing 90% of the total agricultural production, that are generally grown as winter crops (tomato, sweet pepper, cucumber, green beans, eggplant and certain squashes) and summer crops (various muskmelons, watermelons and zucchini) with production peaks in December-January and in May-June (Cantliffe & Vansickle, 2012; Garcia-Caparros et al., 2017). Half of the sweet peppers and a quarter of cucumbers and tomatoes consumed in Europe come from Almería indicates the importance of an all year production (Wolosin, 2008). Despite the economic success, the Almería production system has several structural weaknesses. The fast and intensive horticulture development occurred in the initial stage did not include any kind of territorial planning and organization and generated some negative drawbacks, also because for long time the main objective was to increase the productivity and to maximize the short-term economic gains (Aznar-Sánchez & Galdeano-Gómez, 2011; Aznar-Sánchez et al., 2011) and no attention was paid to environmental issues. In this sense, water quality and management are the most important factors (Castro et al., 2019). Due to overexploitation, water shortage and price increment occurred, while the abundant use of pesticides and fertilizers contributed to contamination of water resources and led to the progressive salinization of the soils (Tout, 1990; Aznar-Sánchez et al., 2011; Cuevas et al., 2019). The solution to these problems was the use of reservoirs and recycled water, progressive adaptation of SCS and the building, at the end of 1990s of two desalination plants (the biggest in Europe) (Colino Sueiras & Martínez Paz, 2002; Galdeano-Gómez et al., 2008; Aznar-Sánchez et al., 2011). The desalination plants are able to supply water for domestic and irrigation use despite the high-energy demand, which is only partially covered by renewable energy resources (Downward & Taylor, 2007). The development of Almería's horticultural sector may be useful in helping other areas to adapt and improve their agricultural systems especially when small-scale farming predominates (Galdeano-Gómez et al., 2013).

1.2. Technical innovation in Tunisian horticultural greenhouses

Many North African countries are affected by the most severe water shortages and by the greatest challenges in terms of future water availability because of the semi-arid climate, limited and variable rainfall and strong water evaporation (Frija et al., 2009). Starting from the 1980s, these countries have developed irrigation infrastructures planning the control of water resources, in order to increase their supply stability given that agriculture accounts for around 80% of the total water consumption (Shiklomanov, 2000; Döll, 2009; Frija et al., 2009; Kummu et al., 2012).

Rainfall in Tunisia varies from less than 100 mm per year in the South to more than 1000 mm per year in the North, which is mountainous and with few cultivable lands. Consequently, most agricultural activities are undertaken in areas with limited rainfall availability, making irrigation and water management necessary for production (Frija et al., 2009). Around 450,000 ha (8% of useful agricultural land) are irrigated in Tunisia (Chebil et al., 2019), providing 35% of the agricultural production value, 95% of horticultural crops, accounting for 22% of agricultural sector exports and 26% of the total agricultural employment (Frija et al., 2009). Greenhouses in Tunisia cover an area of around 8700 ha, and the major horticultural productions derive from tomatoes (Maaoui et al., 2020 and references therein). During recent decades, the growing demand for irrigation water triggered the implementation of collective irrigation systems, promoting user participation, reformulating the water pricing system and stimulating the adoption of water saving technologies at farm level (Al Atiri, 2004). However, irrigated greenhouse production in the Tunisian "Sahel" region has a low irrigation water use efficiency and does not reflect the water-saving oriented policies that have been applied (Frija et al., 2009). At the moment, farmers specializations and technical efficiency of the greenhouse crop production have a negative correlation with the irrigation water use efficiency, which could be improved by enhancing farmer knowledge through better extension services aiming to ameliorate water resource sustainability and productivity (Frija et al., 2009). During drought, groundwater represents one of the major water resources for irrigation (Zairi et al., 2003), especially in coastal zone of Tunisia, where an intensive greenhouse crop production is present. However, it is important to notice that also the groundwater is vulnerable to quality degradation, due to intensive agricultural and anthropogenic activities, and shows a seasonal variability (Khawla and Mohamed, 2020). In addition to water-related problems, in Tunisia there is also a progressive salinization of soils, which is determining the application of SCS. Interesting experiments, for example, concern the use of substrates deriving from "local wastes", as palm trees compost, compost of oasis wastes, and animal manure, or sand and coconut fibre for tomato production (Elabed and Hadded, 2018). Radhouani and colleagues (2011) performed a trial on muskmelon cultivated in soilless system, using sand, and compost of dry palm compared to perlite. These experiments indicate that local substrates allow obtaining good quality products, opening future scenarios more environmentally friendly.

1.3. Protected cultivation system in Israel and the case of the Arava region

Israel's agricultural sector is characterized by an intensive production due to the need to overcome the scarcity of natural resources, particularly water (Regev, 2006). Over half of the country is indeed characterized by arid or semi-arid areas and only the coastal strip and several inland valleys provide the conditions to vegetables production (Regev, 2006). Israel's annual rainfall ranges from 800 mm in the North of the country to 25 mm on the desert edge in the South, from October to April, and the average annual evaporation ranges from 1,400 mm to 2,800 mm (Azenkot, 2006). Although most of the water resources are located in the North and Central part of the country, agriculture and settlements have also been expanded in the South (Azenkot, 2006). This has been possible thanks to the cooperation and interaction between researchers, extension services, farmers and agro-industries which transformed agriculture into a system that is globally renowned for its efficiency and productivity with extensive protected cultivation systems (Gross, 2006; Regev, 2006; Yurista, 2006). Generally speaking, agriculture in Israel reached a very high technological level (Megersa and Abdulahi, 2015). The total area covered with intensive agriculture (greenhouses, shade-houses, and walk-in tunnels) increased from 900 ha in the 1980s to about 13,000 ha in 2012, despite a slight decrease in the total cultivated area in Israel, with 8,000 ha for vegetables production and 5,000 ha for floriculture (Amir, 2006), and an average farm size of 7 ha (Megersa and Abdulahi, 2015). In addition to vegetable and flower crops that have been grown in greenhouses in the last few decades, fruits such as grapes, pomegranates, and citrus are now grown in plastic or net-houses (Amir, 2006) (Figure 5). Thus, production under protected conditions has become the principal way for Israeli growers to ensure a standard, constant, year-round supply of high-quality products allowing exportation to Europe, taking advantage of local climatic and environmental conditions optimizing the use of land, water and chemicals (Amir, 2006). The advanced greenhouse currently used in Israel includes curtains, skylights and shade netting which move automatically in reaction to sunlight. The structures are 5-m high at their lowest point in order to provide best light and working space, while ventilation is provided by the installation of thermal coverings (Amir, 2006). Many strategies have been implemented in recent years to cool the greenhouses during the day and to increase the temperature at night with a minimal investment of energy (e.g. misting/fogging systems have been tested successfully for vegetables and are used for ornamental plants) (Amir, 2006). Research on irrigation systems is ongoing since the early 1950s and it soon became clear that water use efficiency is much higher using pressurized irrigation system compared to surface irrigation (Azenkot, 2006).

Figure 5. Typical net-house in Israel

Water use efficiency is further increased by implementing automatic valves and computerized controllers, using micro-irrigation systems or vegetal indicators such as leaf water potential and fruit growth rate to achieve further precision and regularity in water and nutrient application (Azenkot, 2006). Drip irrigation represents an efficient method of water distribution also in this area of the world (Trifonov et al., 2017 and references therein).

One of the most important weaknesses of the Israel protected cultivated system is that the use of potable water for agriculture was reduced of about 50% on behalf of an increase of the brackish and reclaimed water not only for irrigation of salinity-tolerant crops such as cotton but also for several crops such as tomatoes and melons (Azenkot, 2006). Approximately 25% of greenhouses with SCS have switched to closed/re-circulating irrigation systems by reusing water drainage either back to the same or nearby field being the most efficient, environmental and economical solution to overcome the problem of drought, and which allowed saving 30-40% of water and fertilizer inputs as well. However, this solution would lead to the rise of microbiological hazards if not extensively treated (Azenkot, 2006). Moreover, the application of aquaponic systems is under study in Israel, although the consumer preferences are still under consideration (Greenfeld et al., 2020). This technique could allow to an increase in the production, and to a reduction of waste and energy and, in most cases, of water usage.

Arava is a region in the Negev desert in the South of Israel characterized by extremely hot and arid climate, strong winds and water shortage (Gadiel, 2006). Local groundwater sources are at a depth of 1,000 m, present high salinity level and a geothermal temperature ranging from 35 to 60°C (Gadiel, 2006). Additional water is obtained from the seasonal flooding of streams and collected in reservoirs after rainfall (average 5-35 mm/year) (Gadiel, 2006). Desert silt soil is formed from settled alluvial materials, is completely deficient of organic matter, infertile, and saline. Consequently, the addition of soil from the Arava riverbed allow obtaining the conditions for growing vegetables such as onions, potatoes, peppers, tomatoes, melons, and eggplants (Gadiel, 2006; Trifonov et al., 2017).

Switching from open fields to greenhouses and net-houses productions allowed producing different varieties of crops with high yields and quality able to successfully compete in the international market. Indeed 60% of Israel`s export of fresh vegetables comes from Arava region (Gadiel, 2006). For example, the major crop cultivated in the Arava Valley during winter is sweet bell pepper. Fallik and colleagues (2019) evaluated, for two consecutive years, the effects of water quantity (irrigation water) and quality (salinity) on pepper yield and fruit quality, also in post-harvest. They concluded that fruits cultivated in greenhouse and irrigated with moderately saline water, of EC 2.8 dS m^{-1}, still maintain a good quality. On the other hand, higher salinity levels significantly affected, in a negative way, both pepper yield and postharvest quality. This reminds us that the cultivation phase is crucial for the final quality of the produce, which is obtained in the field.

1.4. Australian low-cost hydroponic greenhouse for cucumber cultivation

In Australia, as in many other developed economies, irrigated horticulture has increasingly moved from small farm, to large, highly specialised and intensive production systems. This results in a growing demand of water. Agriculture represents 67% of total water consumption in Australia (Hickey et al., 2006). The Australian greenhouse industry is dominated (up to 80%) by low-cost simple structures using TCS, other media or SCS and the hydroponics system for supply water and nutrients to plants (Grewal et al., 2011).

Low-cost greenhouse and hydroponic producers of cucumber and tomatoes have great potential to improve water and nutrient use efficiency because the greenhouse production input re-use is very limited due to the risk in microbial infections or reduced yield due to a non-optimal management of the water and NS (Grewal et al., 2011). Since drainage water contains nutrients, it can in fact contribute to the pollution of local waterways (Thompson et al., 2007). Grewal et al. (2011) reported a study on the opportunities of using the recycle in a commercial farm in Londonderry - New South Wales, Australia. Farm is organized with 18 greenhouse tunnels (12 used to produce cucumbers and 6 to tomatoes), each one with an area of 450 m^2.

The cultivation described in the trial was conducted with a hydroponic system in which the NS (water and minerals) was distributed through drippers to the plants. Plants were growing in black plastic bags filled with a potting mixture. The study showed that in cucumber greenhouse growing system, 38% of the total irrigation water applied was used by the plants and the remaining 62% was discharged from the greenhouse as drainage water. The reuse of the drainage NS resulted in 33% saving of the total potable water for cucumber production and in the reutilization of 566 kg/ha N, 25 kg/ha P and 703 kg/ha K which was used both for cucumber and for other crops, preventing its discharge into the local environment (Grewal et al., 2011).

This case study demonstrates that some relatively simple changes and not too expensive technology in irrigation practices within greenhouse systems can considerably improve sustainability of low-cost hydroponic greenhouses helping to minimise the environmental footprint (Grewal et al., 2011).

2. Temperate Regions

Soilless cultivation is practised in large scale in arid regions, as reported in the previous section, but this technique is not only useful in case of water scarcity, low quality water and/or lack of fertile soils.

In fact, currently, hydroponic cultivation is receiving great attention worldwide thanks to very efficient resources management and to the high yield and quality of food production without forgetting the safety of vegetable produce as well (Tzortzakis et al., 2020). Moreover, this kind of systems can be applied with the aim of cultivating in areas with scarce availability of arable land, or even within big cities/metropolis (Kalantari et al., 2017). We are looking at the diffusion of numerous indoor farms (or vertical farms, or plant factories) in this context (Pennisi et al., 2019 a).

Vertical farms allow growers to obtain good production in small areas, also in multiple layers, with less inputs (mostly water and nutrients). There are examples of successful cultivation of various species including leafy vegetables (Figure 6), aromatic plants, microgreens, saffron, mushrooms (Figure 7), strawberries, among others.

Focusing on water consumption, as reported by several authors, vertical farming allows to a real water saving. As an example, lettuce plants growth with conventional method, require around 250 L/kg/y, while hydroponic system showed an estimated water demand of 20 L/kg/y (Barbosa et al., 2015).

Figure 6. Greenhouse vertical farming for lettuce in SCS in Mexico

Figure 7. Indoor vertical farming for mushroom in Iran

In Italy, trials related to the influence of LED lighting on the resources use of lettuce cultivated indoor were conducted (Pennisi et al., 2019b); results suggest an efficient use of water (WUE up to 75 g FW L^{-1}) with a red: blue ratio of 3. Similar information is provided by experiments on basil (Pennisi et al., 2019 a), that showed the greatest WUE in plants grown under a red: blue ratio of 2 or 3 (average value of 44.5 FW L^{-1}).

SCSs in Italy are also applied in leafy vegetables cultivation to save natural resources and mitigate the problem of nitrate accumulation (Santamaria et al., 2001; 2002; Fontana and Nicola, 2009; Cavaiuolo and Ferrante, 2014) (Figure 8). This issue increasingly attracts the attention of producers, companies, and researchers.

In Italy, and especially in the South, tomato is a very widespread crop used for greenhouse cultivation.

Figure 8. Leafy vegetables (basil) in SCS in Italy

Valenzano and colleagues (2008) compared the cultivation of tomato in soil with two hydroponic systems: (NFT; closed cycle) and on rockwool substrate (open cycle). Regarding WUE, the NFT system allowed minimizing the use of water than other systems. Signore et al. (2016) studied, through the use of a closed soilless system, the way to minimize the environmental impact of tomato plants growth in greenhouse and at the same time reduce the accumulation of ions in the recycled NS. SCSs are also used for strawberry production in open and closed-growing systems. Yield and quality of fruits can be higher especially during the unfavourable seasons. Moreover, the cultivation can be carried out 1-1.5 m above ground, improving the harvesting operations (Nin et al., 2018). Indoor cultivation experiments with different lighting systems showed that blue light provided with LED induced higher yield, without effect on the quality parameters (Nadalini et al., 2017). In strawberry cultivation, as reported in a Romanian trial, SCS could be also an effective method to prevent root diseases (Adela et al., 2013). Aromatic and medicinal plants are other crops that can be grown in hydroponic and aeroponic system, allowing to obtain a greater concentration in bioactive molecules (Hayden et al., 2002; Giurgiu et al., 2015), high yields, and production with minimum residues of pesticide (Rachappanavar et al., 2019). In Romania, studies on basil and mint cultivated in three different hydroponic systems (one horizontal and two vertical) revealed that the considered species were positively influenced by this kind of crop system, in terms of mineral content and nutritional quality, ensuring an optimal use of the resources (Dobrin et al., 2018). In this geographical area, SCSs are also applied for the cultivation of: cucumbers, as reported by Sorin et al. (2015) in a trial on perlite substrate; lettuce plants grown with NFT (Drăghici et al., 2016); tomatoes on mattresses filled with perlite (Drăghici et al., 2013).

CONCLUSIONS

The application of highly specialized farming like greenhouses equipped with SCSs offers the possibility to grow horticultural crops in any kind of environment, including marginal and arid lands that conversely could not be used for agricultural purposes. Moreover, innovative growing systems allow maximizing the yield and extending the growing season due to the possibility to control several environmental factors (i.e. light, temperature, humidity) and to the improvement of nutrients and water use efficiency. Therefore, the economic and environmental sustainability of these intensive cultivation systems is improved. The need for increasing the crop productivity of certain arid and desert areas stimulated the development of innovative and advanced technological solutions that allowed overcome the limitations due to sub-optimal environments. This technological improvement contributed to the creation of a novel perspective and opened new possibilities in crop production, allowing a more rational use of agricultural resources, also in those areas characterized by less challenging environmental conditions.

Today horticulture must face a series of rapid changes in order to adapt to the environmental, economic, and social challenges that the world is experiencing. Thus, the application of highly specialized cultivation techniques can represent an efficient system to increase food security and sustainability in areas where both land, water and crops are scarce as well as in more temperate/favourable regions. New frontiers of SCS application are represented by the indoor vegetables production in urban and peri-urban environments. These applications require an implementation such as the use of ICT for real time crop managements and environmental control. Lighting can be considered a production factor with the possible modulation considering the crop needs during cultivation. In this context, the awareness of growers, supply chain partners, research institutes and governments toward technical and socio-economic aspects of greenhouses and SCSs is fundamental for the future development of horticulture.

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