Implementing Sustainable Irrigation

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The sustainability of irrigated agriculture is threatening due to adverse climate change, given future projections that every one in four people on Earth might be suffering from extreme water scarcity by the year 2025. Pressurized irrigation systems and appropriate irrigation schedules can increase water productivity (i.e., product yield per unit volume of water consumed by the crop) and reduce the evaporative or system loss of water as opposed to traditional surface irrigation methods. However, in water-scarce countries, irrigation management frequently becomes a complex task. Deficit irrigation and the use of non-conventional water resources (e.g., wastewater, brackish groundwater) has been adopted in many cases as part of a climate change mitigation measures to tackle the water poverty issue. Protected cultivation systems such as greenhouses or screenhouses equipped with artificial intelligence systems present another sustainable option for improving water productivity and may help to alleviate water scarcity in these countries. This article presents a comprehensive review of the literature, which deals with sustainable irrigation for open-field and protected cultivation systems under the impact of climatic change in vulnerable areas, including the Mediterranean region.

evapotranspiration | water use efficiency | protected cultivation | precision agriculture | screenhouses

The present report summarizes sustainable irrigation management guidelines in water-scarce regions. In particular, as climate change are increase the intensity and frequency of extreme events; more resilience from people and society is required. Over the longer term, intensive drought events, water scarcity, overexploitation of groundwater resources and water quality issues remains much-less the same between regions in arid and semi-arid climate. Several countries have already developed extensive legislation, institutional capabilities actions and practices that are required for the effective climate change adaptation. Good irrigation and water management practices are highlighted with the aim of transferring knowledge in regions which are in the stage of developing national schemes regarding water productivity optimization. It has to be noted that no individual measure or action could effectively tackle water scarcity issue.

1. Introduction

It is projected that by 2080, net crop water requirements will increase globally by 25% despite the increased irrigation efficiency, attributed to changes in precipitations patterns, global warming, and extended crops' growing periods [1]. Nowadays, extreme weather events such as frost, hail, heat waves, percentile of precipitation, and drought periods affected global food security, limiting rain-fed and irrigated agricultural crop production potential [2][3][4][5]. Mediterranean countries have been identified globally as climate change "hot spot" areas where the occurrence of hot extremes is expected to increase by 200 to 500% due to elevated greenhouse gas emissions [6][7]. Indeed, crop water demands are relatively high, especially in arid and semi-arid areas, due to high radiation load observed throughout a year, but also in more temperate and sub-tropical zones as periodic drought phenomena and heat waves often occur [5]. Reference evapotranspiration (ETo; the sum of evaporation from the soil and transpiration from a reference crop such as, e.g., grass or alfalfa) is expected to increase in many parts of the world by 2055, increasing the total irrigation water needs [8]. In Spain, under Mediterranean climatic conditions, irrigation water requirements are expected to increase between 40 to 250%, depending on the crop type by 2100 [9]. In Cyprus, a typical water-scarce country with the highest water stress index among European countries, for the period 2031–2060, the seasonal average temperature is expected to increase by up to 2°C for winter, 3°C for summer, and 2.4°C for the transient seasons; in addition, a mean annual decrease in total precipitation of 5 to 15% is expected [10]. Actually, for a given type of soil and crop, both annual and seasonal rainfall variations are critical for the estimation of a predictable water stress profile which can be addressed [11]. For example, the phenological behavior of rain-fed winter wheat (*Triticum aestivum* L.), which is considered to be an important crop grown in the Mediterranean, is expected to be negatively affected by variations in rainfall patterns, resulting in yields reduction [12]. This is especially true as agricultural water demand is less flexible, while the supply is at or beyond the margin of sustainability, so there is a limitation of crops' abilities to absorb variations in the water supply [13].

Modernization of irrigation increases the water application efficiency. Converting from traditional surface irrigation methods to closed pressurized pipe network systems could lead to as much as 90% of the total water savings, as is the case of trickle irrigation [14]. Therefore, the use of improved irrigation schemes was financially supported through the World of Bank in low-income countries with the aim of reducing poverty. In the European Union, improved irrigation systems are of the priority measures of the European Water Framework Directive for achieving irrigation water sustainability [15]. Nowadays, 40% of the world's food comes from the 18% of the cropland that is irrigated, while in several cases, high water application efficiency irrigation systems estimated to be used in more than 95% of the total irrigated land as is the case of Cyprus [16][17]. Overall, in Mediterranean countries, the irrigated area accounts for less than 40% [18]; however, in Germany, only 2% of the cropland area are irrigated [19].

On the other hand, the traditional assumption that substantial water savings may obtain through the adoption of new/improved technology irrigation systems are under controversy in some instances. This is a consequence of higher irrigation systems' application efficiency, which tends to increase their irrigated area, in addition to less irrigation return flow back to the aquifers. Therefore, the total water consumption calculated on a basin scale increased [13]. Similarly, climatic and economic implications of the modernizing irrigation system are related to the high energy use and carbon emissions for extracting groundwater, pumping it, and distributing it in the appropriate water quantity and pressure [20]. In another occasion, the Chinese government is planning for the expansion of irrigated areas by 4.4% until 2030 [9] under the concept that global irrigation patterns seem to alter climate with some cooling effects observed near irrigated areas during the peak period of irrigation [21][22]. However, in the Mediterranean region, soil salinization and land degradation are often associated with irrigated land [5][20]. Worldwide, it is estimated that by 2050, more than 50% of arable land will have soil quality issues, while at the current time, about 10 million hectares are abandoned every year due to soil salinization [23].

In any case, irrigation scheduling frequently represents a difficult task to accomplish, resulting in significant water losses [24]. Traditionally, irrigation scheduling was based on growers' perspective rather than on climatic characteristics, soil properties, or plant indicators, resulting many times in over-irrigation of crops. Consequently, water and nutrients depleted and potentially lead to groundwater contamination [25]. Indeed, in the Salinas Valley of California, irrigation of vegetables was estimated as 200% above actual crop evapotranspiration [26]. In any case, excessive irrigation is associated with the lack of root aeration and favors plant pathogens [27]. However, it is generally accepted that the use of evapotranspiration models in irrigation practice increases the efficiency of water and nutrient application. In fact, in intensive production systems such as soilless culture systems, irrigation control requires the estimation of crop evapotranspiration over short time intervals, e.g., in the basis of a few minutes [28]. Therefore, more sophisticated/complex irrigation monitoring systems are required with the aim of matching the diurnal evapotranspiration fluctuation with water and nutrient supply. Even in the latter case, there is a need for models' recalibration under prevailing climatic conditions.

Agronomic practices such as "deficit irrigation" (i.e., irrigation application below evapotranspiration) save water and enhance water use efficiency (WUE) of the crops as a result of an improved ratio of carbon fixation to water consumption ratio [29]. In addition, as biomass production and transpiration are tightly linked to each other and both are facilitated by stomata pores, the effective use of water under limited water condition should be the aim of maximum soil moisture capture with minimal water losses by stomata transpiration and soil evaporation [30]. Plastic film mulching has been shown to decrease soil evaporation [21]. In line, protected cultivation systems (greenhouses, screenhouses) have been proved to have higher WUE values comparing with open-field cultivation [31]. Indeed, peppers' water requirements under the screen cover were found to be 38% lower than those of an open-field crop affected by lower evapotranspiration rate [32]. In addition, the water productivity (WP; the ratio of the total value of production to total crop irrigation water supply, € m^{-3}) of protected crops is much higher as opposed to open-field crops' due to the higher economic value of crops that are produced out of season [33]. Katsoulas et al. [34] have demonstrated that increasing the greenhouse cooling system capacity gives higher values in yield in both in the Mediterranean and Central European countries.

Rural areas are expected to experience major impacts of climate change on water availability and supply; infrastructure and agricultural incomes; reduced agricultural production; and food security with socioeconomic consequences, such as increasing poverty and migration. Farmers only recently start to adopt water-saving practices and technological improvements in irrigation. The adoption is relatively low because in many cases, these systems are of high cost and growers do not benefit directly by water saving [35]. Thus, sustainable irrigation adaptation to climate change in water-scarce regions should be implemented in terms of demand and supply enhancement of water management, even though measures are often linked through the hydrological cycle.

Increasing the productivity of water, the use of non-conventional irrigation waters, crop diversification, and crop rotation are some of the adaptation/mitigation measures discussed in the following. Reliable estimates of consumptive use are especially needed for water allocation by policy makers at the basin scale and beyond and for optimizing farm irrigation management under water scarcity. Anyhow, it is important to understand that implementing sustainable irrigation in water-scarce regions will be feasible only by a combination of measurements, rather than by individual actions.

2. Improving Irrigation Efficiency

The majority of irrigated land in the world is of the category surface irrigation. The field water application efficiency of traditional surface irrigation methods such as, e.g., furrow, basin, or border strips (Figure 1) is estimated to be as low as 40% [36] with excessive deep percolation losses and low water distribution uniformity [37]. However, in countries with the largest irrigated area, these methods are prevailing because they are low-cost and easily implemented.

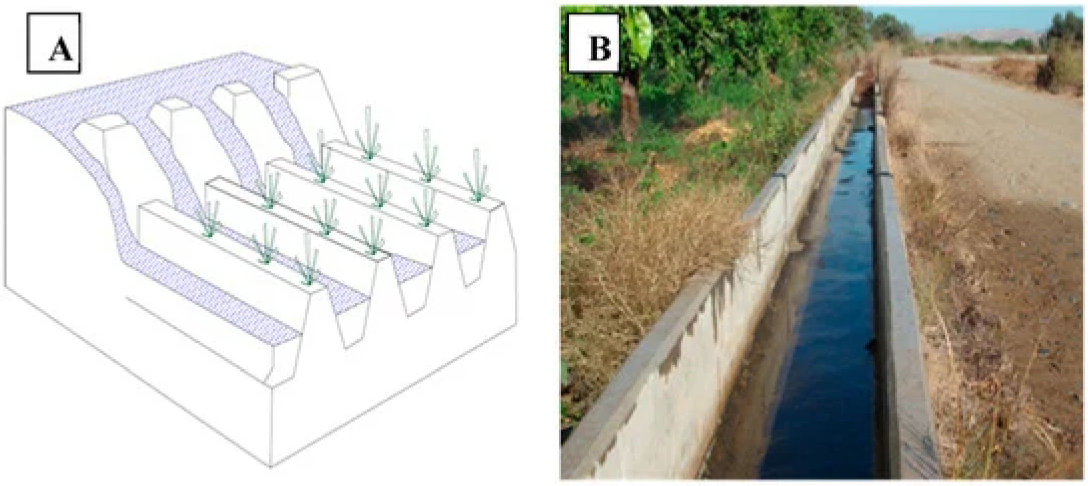

Figure 1. Traditional surface irrigation method (furrow irrigation, (**A**)); open canal water distributing network (**B**).

Selecting the appropriate irrigation method will be advantageous to manage limited water supplies and increase crop profitability [38]. Nowadays, it is widely accepted that a pressurized irrigation system (PIS; an installation under pressure network consisting of various pipes, valves, and fittings for supply water from the source to the irrigable area) [39] has significantly higher water application efficiency values as opposed to traditional irrigation methods such as, e.g., furrow and border strips. PIS operate on demand, which allows for higher irrigation frequency, optimization of crop irrigation scheduling, and cropping pattern diversification [13]. The application of fertilizers can also be optimized through fertigation (i.e., irrigation combined with fertilization). A typical arrangement of PIS pipe layout and irrigation components indicated in Figure 2. The control head unit is considered to be the most important part for measuring and appropriately treating the irrigation water [40].

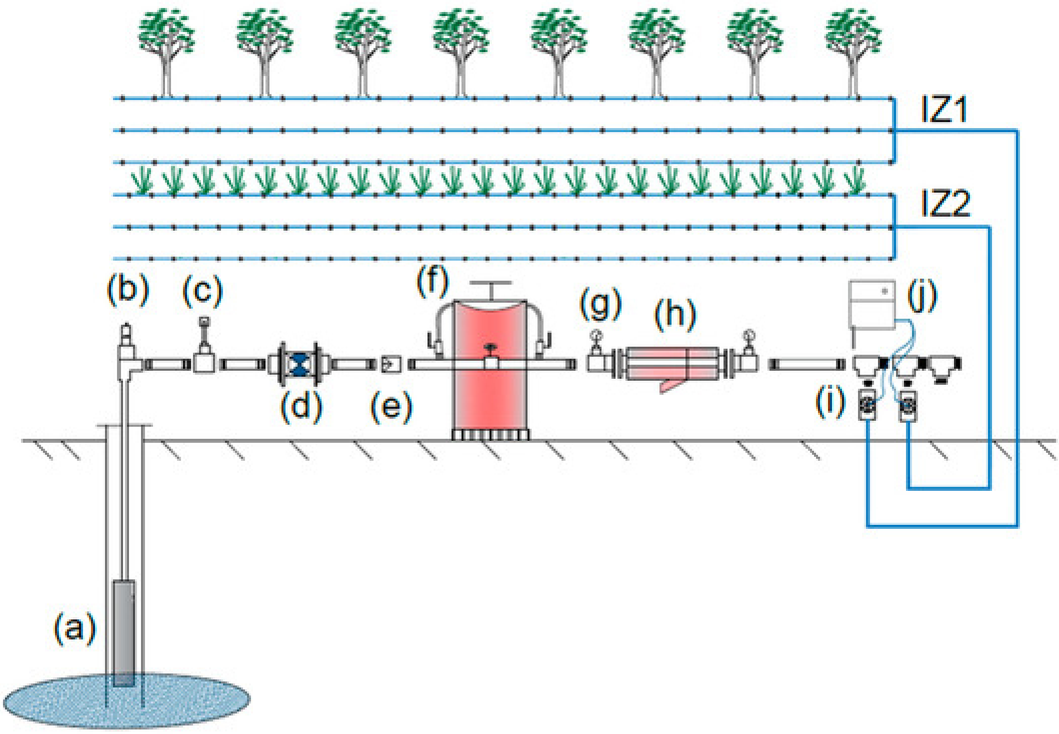

Figure 2. Layout components of a modernized pressurized irrigation system (PIS); supply pump (**a**); central control head unit ((**b**) to (**h**)); pressure regulator and pressure relieve valve (**b**); air release valve (**c**); water meter (**d**); one-way valve or a non-return valve (**e**); injection tank (**f**); pressure gauge (**g**); filtration unit (**h**); manifold and electric valves (**i**); irrigation zone 1 and 2 irrigating crops with different water needs (IZ1,IZ2); irrigation controller (**j**).

Plastics, as the basic component of PIS, were first produced in British industry in 1935, even though the idea of using plastic pipes for irrigation become feasible during the World War II [41]. Early advances in surface drip (i.e., trickle) irrigation technology, which is considered to be the most efficient irrigation method in terms of water use, took place in Israel from the 1950s into the 1970s [22], although, according to Velasco-Muñoz et al. [42], drip irrigation systems application was first recorded in Australia in the 1940s. Aside from the fact that the installation of PIS remains costly and requires specific skills and knowledge to operate, it is still an important adaptive strategy to reduce agricultural risk during times of drought [43]. However, in humid areas, the application of PIS may not be profitable if droughts are rare [37]. Over the past decades, a significant shift to pressurized irrigation was observed, with a significant component being micro-irrigation, including micro-sprays, mini-sprinklers, surface drip, and subsurface drip irrigation systems (SDI) [44].

Particularly, the field application efficiency is about 50–70% with sprinkler system and 80–90% with surface drippers [45]. That is because as drip irrigation system minimize water losses due to surface runoff and deep percolation of water under difficult soil and terrain conditions [22]. Water is locally applied directly near to the root zone in low application rates and pressure and enables the precise management of soil moisture. Due to the low operating pressure of drippers (e.g., 100 kPa), the energy cost is also decreased compared to the sprinkler system (e.g., micro-sprinkles 200 kPa, spray booms 500–600 kPa) [39][44][46]. Thus, low pressure irrigation systems will result in both water and economics savings [47]. However, in such a case, it is important to assess water quality as lower operating system pressure, increasing the possibility of clogging drippers [46]. The appropriate selection of filtration system based on the water source will ensure the good operating performance of irrigation systems (Figure 3). In any case, drip irrigation can minimize the wetting of leaf surface and thus the risk of leaf sunburn and crop diseases, while sprinkling result in wet leaves and mud splash [48]. In addition, drip irrigation is preferable when recycle water is used, as there is also minimization of the risk of pathogen movement to the crops. Choosing the appropriate irrigation method should also take into consideration several factors such as the soil infiltration rate, the system precipitation rate, and the quality of water. In any case, the main problem of PIS has to do with poor hydraulic design, resulting in low field application water uniformities [49]. Qi et al. [50] concluded that the effects of different irrigation water movement in soil crack closure and soil water storage efficiency were lower in drip irrigation rather than in sprinkler or in surface irrigation. HYDRUS models have been repeatedly used in the literature e.g., [51][52][53] for simulating irrigation soils' water movement and other related options.

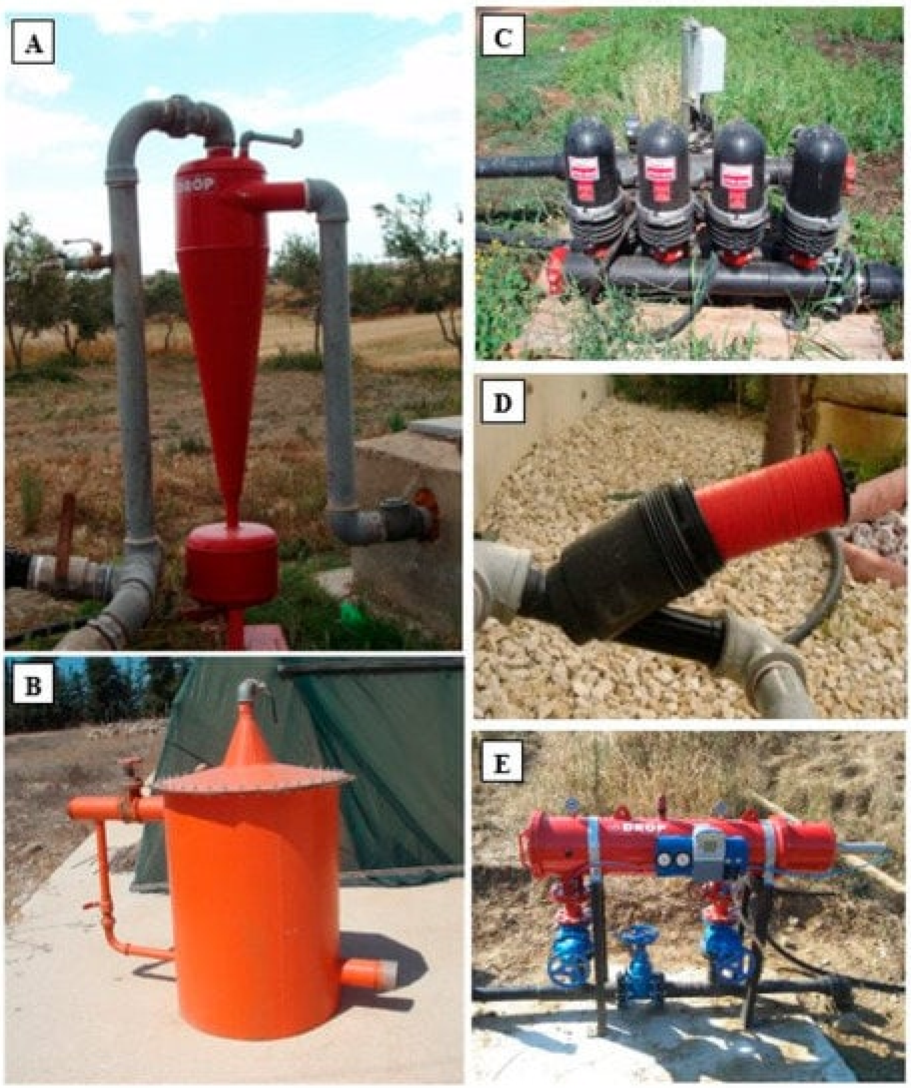

Figure 3. Different types of filters; a hydrocyclone device used for water and sand separation (**A**); a sand–gravel filter used for algae and organic matter removal, usually from an open water reservoir (**B**); a series of an automatic disc filter system (**C**); a manual disc filter (**D**); an automatic self-cleaning filter with a self-cleaning backwash mechanism (**E**).

Drip irrigation systems account for up to 90% application efficiency, and they have been used with success in arid and semi-arid regions for vegetable production, forage crops, and maintenance of trees [54][55][56]. Yield of onions almost doubled using SDI, allowing for more frequent irrigation with smaller depths of water [38]. In tomatoes, the most appropriate irrigation arrangement for optimum growth and production is considered to be SDI with plastic film mulching, according to Wang et al. [57]. In any case, water savings of up to 20% were recorded in olives under the SDI treatment as opposed to surface drip irrigation [58].

In another occasion, irrigation sustainability may not always be in accordance with environmental sustainability. Recent work raised a few controversial thoughts that policies of encouraging the adoption of more efficient irrigation technology will potentially lead to the cultivation of more water-intensive crops on previously marginal land, in addition to less irrigation water return flow to the watershed, a phenomenon known as “irrigation paradox" [59][60]. Furthermore, the irrigated area could be increased by 30–40% when shifting from furrow to sprinkler and drip irrigation systems [45].

3. Measures for Sustainable Irrigation and Water Management Recommendations in Water-Scarce Regions

- Adoption of improved high water application efficiency pressurized irrigation system. Frequent system inspection and irrigation systems' maintenance. Irrigation combined with fertilization should also be promoted,
- Appropriate irrigation scheduling based on local conditions,
- Application of low-cost commercial sensors and irrigation controllers (on-farm irrigation management and control technologies); adopted by smallholding aged farmers with low level of technical education [61],
- Big data analysis and artificial intelligence system for implementing precision irrigation for new age farmers with are familiar with technological improvements [62],
- Volumetric water metering and water pricing in each plot. Temporary drought surcharges rates for over-irrigating crops should be promoted [16],
- Groundwater aquifer extraction should be protected appropriately. Drilling wells to access groundwater must require a permission taking into account water quantity and quality issues,
- Adopting water prices that induce farmers to irrigate by night [63] in selected crops,
- Increasing the frequency of irrigation can be helpful for salinity management. Frequent irrigation requires high labor inputs, therefore economic considerations usually favor automated or mechanized irrigation systems [64],
- Leaves wetted by sprinkling water absorbs salts directly; therefore, sprinkler irrigation at night is preferable,
- Reducing water evaporation from open reservoirs (Figure 4) using chemicals films and flooding objects and reduce soil water evaporation with crop residues, plastic mulches etc,
- Enable growers to adopt cropping systems with recycling of the excess irrigation water. Re-use of drainage water especially in large irrigation schemes [65],
- Training growers in operation and management of water savings programs, such as deficit irrigation strategies,
- Selected drought resistant varieties, taking into consideration seasonal rainfall availability. The adaptation of planting dates i.e., after a rainy season ensures more effective conditions for crop establishment [64],

- Established on farm water storage capacities like reservoirs and tanks, for water harvesting, and reused it for irrigation. Practices like terracing construction and small dams can be used to increase aquifer recharge [63],
- Enhance the productive use of rainwater (Figure 7) by supporting sustainable land management and farming methods that increase soil organic matter and improve the water infiltration and water retention capacity of soil [64],
- Develop an Agricultural Insurance Law that includes drought hazards, considering droughts as a natural disaster, therefore developed a legislation to implement competencies and action of public institutions to face a natural disaster [65],
- Protected cropping systems increasing the WUE values. Proper design and operation of climate control within these structures under local conditions, ensures minimum operational cost, enable of controlling crop evapotranspiration and drainage emissions without compromising yields,
- In rain-fed agriculture, enhanced production, and imports of food product through international trade. The concept of 'virtual water' indicated that gains in water productivity can be achieved by growing crops in places where climate enables high water productivity at lower cost and trading them to places with lower water productivity. Although rarely expressed in water terms, virtual water trade is already a reality for many water-scarce countries, and is expected to increase in the future [65],
- Increasing consumption of meat and, to a lesser extent, also dairy products translates into increased water consumption, as their production requires large volumes of water. The extent to which societies are willing to modify their diets as part of a larger effort to reduce their environmental footprint reaches far beyond water scarcity concerns. Yet, it has implications in terms of national food security and associated water-scarcity coping strategies [64],
- Reduction of water losses in the postharvest value chain (i.e., blue water footprints). Indeed, more than one-third of food is lost or wasted in postharvest operations, therefore it could be a sustainable solution to reduce the pressure on natural resources [65],
- Using newly accessible technologies and strategies to achieve high water use efficiency and to promote non-conventional water resources (e.g., wastewater, salt-contaminated) in combination with soil fertility,

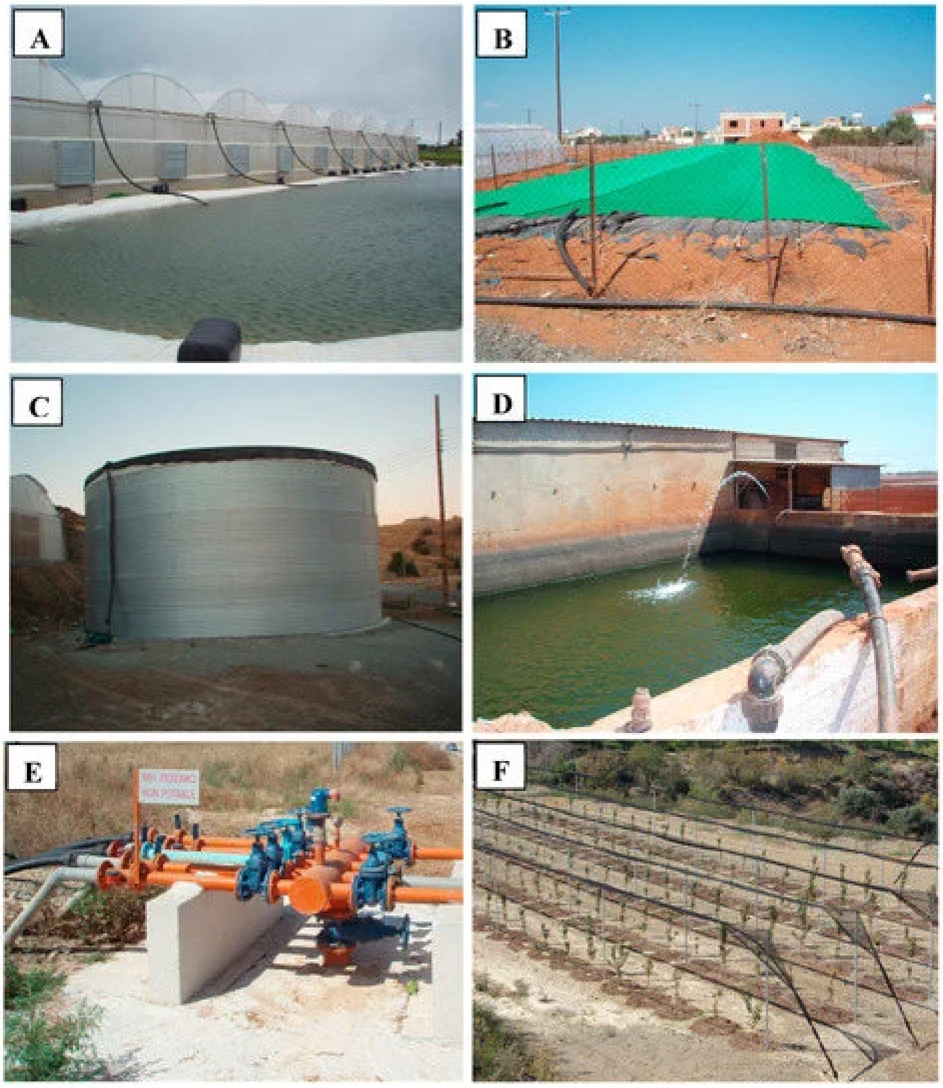

Figure 4. Rain water harvesting and storage in open reservoir (**A**); water storage in a covered reservoir minimizing water evaporation losses and algae growth (**B**); a commercial closed water reservoir (**C**); blended water from different sources (**D**); a water supply main manifold of recycle water (**E**); localized irrigation and net protection in a tree cropping system (**F**).

4. Conclusions

The present report summarizes sustainable irrigation management guidelines in water-scarce regions. In particular, as climate change are increase the intensity and frequency of extreme events; more resilience from people and society is required [65]. Over the longer term, intensive drought events, water scarcity, overexploitation of groundwater resources and water quality issues remains much-less the same between regions in arid and semi-arid climate. Several countries have already developed extensive legislation, institutional capabilities actions and practices that are required for the effective climate change adaptation. Good irrigation and water management practices are highlighted with the aim of transferring knowledge in regions which are in the stage of developing national schemes regarding water productivity optimization. It has to be noted that no individual measure or action could effectively tackle water scarcity issue.

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