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Review

A Critical Review of Innovations and Perspectives for Providing Adequate Water for Sustainable Irrigation

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Abstract: Global climatic change intensifies the water crisis, particularly in arid and semi-arid regions. In this regard, the provision of enough water for irrigation is a serious dilemma because the agricultural sector consumes the largest amount of water (70% withdrawal and 90% consumption). In this review, we have summarized recent innovations that have emerged as unconventional techniques to supply adequate water for irrigation purposes. We present the principles and basics of seven approaches: the Sahara Forest Project (SFP), water extraction from the air (WEA), aquifer recharge, the treatment of marginal water using a magnetic field, desalination and wastewater treatment (DWT), electro-agric technology (E-AT), and the Toshka Project. The SFP is currently being utilized in Aqaba, Jordan, and DWT is considered a common practice worldwide, whereas some of these innovations are still under investigation to ensure their feasibility for large-scale applications, such as E-AT. The Toshka Project is considered a wonderful idea that utilizes the water stored behind the High Dam in Lake Nasser, Egypt. Several approaches have been adopted to reduce the amount of water being used for irrigation, as the current amount of freshwater is insufficient for the requirements of increased agricultural consumption, particularly in hot, arid, and semi-arid regions.

Keywords: water crisis; irrigation; water production; practices and perspectives; climatic change

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1. Introduction

Many countries will be affected by climatic change, especially those located between 10° and 50° N, and are expected to suffer from a limited supply of water from 2070–2099 relative to 1961–1990. This problem worsens with the annual increase in the world population and simultaneous increase in water demand by urbanization, agriculture, and the industrial sector [1,2]. Water scarcity issues have become more complicated with global climate change (e.g., desertification) scenarios and the variability of precipitation and increasing drought indices throughout agricultural zones worldwide. Moreover, in the recent future, the global water requirements are expected to increase to 160% of the currently available water resources by 2030 [1,3–5].

Villar-Navascués et al. mentioned that the current water availability is anticipated to decrease by 20% in 2070 owing to climate change and the surface area of water stress conditions is expected to increase from 19 to 35%. Thus, it is predicted that if the next World War occurs, it will be over water resources [6]. Over 2 billion people are living with constant water shortages, and approximately 4 billion people suffer from severe water scarcity for at least one month every year [7]. Globally, there are approximately 20,000 facilities being utilized for desalination and >300 million people use desalinated water [6]. Approximately 60 countries currently reuse water for irrigation, and Israel is leading the way in this process by reusing 400 million m^3 of water reclaimed from agricultural purposes [8,9]. Water reuse is important because there is concern over climate change scenarios, which are anticipated to make arid regions drier, and rainy regions wetter and more humid [8]. In the arid and semi-arid regions, the topic of scarcity issues is more obvious, such as the Middle East and North Africa region, and by 2050, it is predicted that the economic losses of these regions will reach 6–14% [10].

Irrigation consumes the highest volume of global freshwater (70% withdrawal and 90% consumption), and this issue is becoming more complicated because 56% of irrigated crops worldwide are located in regions that are characterized by extremely high water stress [3,8]. Reclaimed water is globally utilized for agricultural purposes; however, the amount reused differs by country (e.g., 46% in California, 32% in Asia, 44% in Florida, and 7% in Japan). Moreover, reclaimed water accounts for 44% and 25% in southern Europe and Tunisia for irrigation, respectively; 51% in northern Europe for environmental applications; and 25% in Spain for agriculture. Australia uses reclaimed water for only 4% of the total water demand. Singapore fulfills its water demands by reusing 30% of treated wastewater, and this quantity is anticipated to increase to 55% by 2060 [3,9]. Approximately 90–97% of wastewater is reused in Cyprus and 78% in Oman [10].

This study introduces the innovations (practices and perspectives) that provide or make unconventional water supplies suitable for irrigation purposes. From our literature survey on several scientific research engines, we did not find relevant publications that focused on surveying recent innovations dedicated for providing solutions to secure enough irrigation water to assist the agricultural sector and secure the production of food and feed. Based on literature survey, there are seven approaches that have been investigated (Figure 1): (1) the Sahara Forest Project (SFP), (2) water extraction from air (WEA), (3) aquifer recharge (AR), (4) the treatment of marginal water using a magnetic field (MF), (5) desalination and wastewater treatment (DWT), (6) electro-agric technology (E-AT), and (7) the Toshka Project (TP). However, before presenting the principles and basics of these approaches, we present a summary of approaches that have been used for reducing agricultural water demand and/or improving water-use efficiency. In addition, the current situation of global vegetation and precipitation is also discussed to illustrate the importance of the present review.

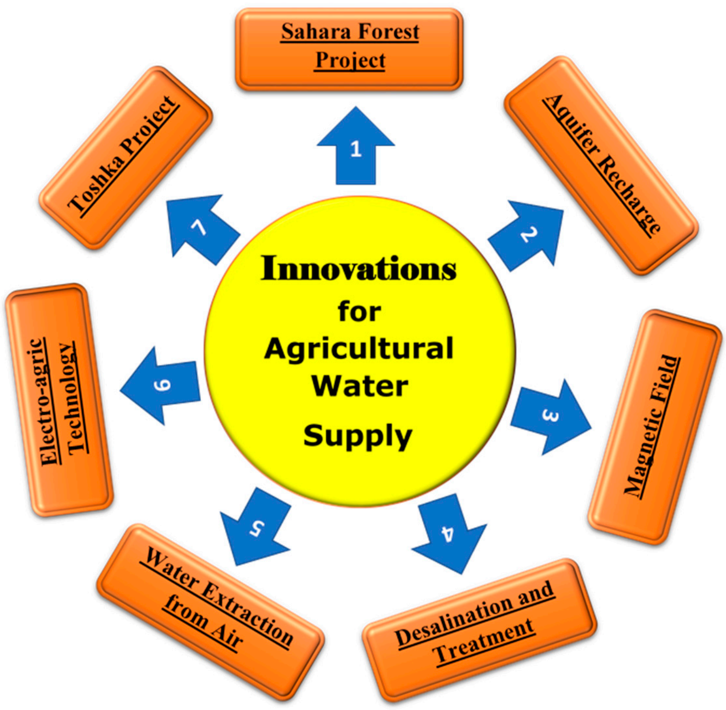


Figure 1. Innovations for providing unconventional water supply suitable for irrigation.

2. Summary of Approaches Proposed to Reduce Agricultural Water Demand and/or Improve Water-Use Efficiency

Agricultural activities consume large amounts of water [1,3,8]. Although, traditional irrigation approaches such as flooding irrigation are still used in some regions (i.e., China) [1], several innovations have been introduced to improve water-use efficiency and reduce agricultural water consumption, as shown in Figure 2.

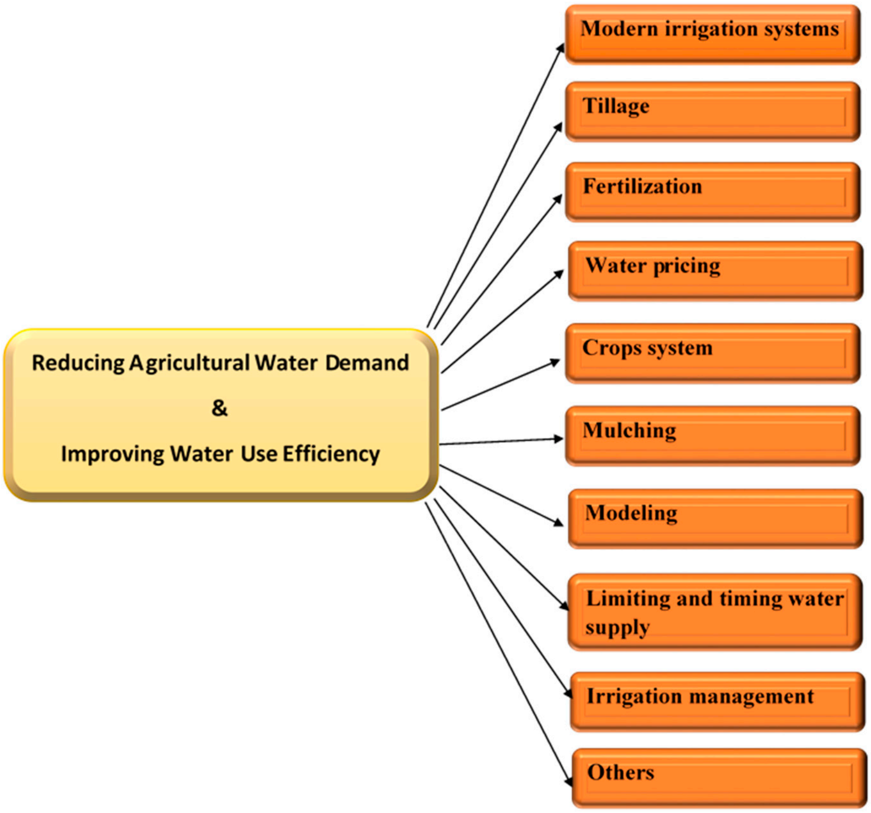


Figure 2. A schematic diagram shows the approaches used for reducing agricultural water demand or/and improving water-use efficiency.

The processes that have been proposed to reduce the water consumption of the agricultural sectors include several modern irrigation approaches, such as mobile drip irrigation (possesses the integrated efficiency of drip irrigation and the versatility of center-pivot irrigation) [11], center pivot [12], ebb-and-flow sub-irrigation benches [13], and other smart irrigation monitoring and control strategies that have attached advanced wireless monitoring systems [4]. Moreover, it was reported that the ridge–furrow optimization ratio with the addition of nitrogen resulted in increased water-use efficiency and grain yield for rainfed spring maize in the Loess Plateau region of China [14]. Qiang et al. reported that tillage and irrigation management plays an important role in plant water availability. The controlled-release urea of rainfed spring maize in northern China at a certain depth (16 cm) represented a better balance between agronomic and environmental benefits [15]. Agricultural water withdrawals can be reduced if a pricing perspective is applied; for example, a 1.7–9.5% reduction in withdrawals may be achieved, while reducing profit by between 4.9 and 5.6%, ultimately increasing the water tariff revenue by 57–65 times [16]. Adapting special crop systems, such as the following winter (i.e., forgoing winter wheat production), assists in increasing the replenishment of groundwater in the Hebei Plain (China); however, this approach can negatively affect the annual production of wheat [17]. Cropping systems vary in their unit irrigation water consumption, which makes it feasible to decrease total irrigation water consumption by optimizing cropping systems.

Approximately 12% of global water consumption from irrigation could be decreased if we reshaped the global distribution of crops within the current rainfed and irrigated croplands. In addition, approximately 23% of irrigation water consumption could be reduced using an optimized crop pattern and irrigation water quota (e.g., the Yingke Irrigation District in the Heihe River Basin of China) [1]. The agricultural mulching approach has also played an important role in ensuring the sustainability of cotton, providing an the irrigation water possesses salinity of under 5.4 dS·m^{-1} [7]. Straw mulch together with the application of chemical fertilizer (125% of the state-recommended dose of chemical fertilizers) and surface irrigation leads to enhanced water productivity, soil fertility, and cabbage yield [18]. It was reported that the use of the mulching approach is highly capable of reducing the blue water footprint by 3.6%, whereas the integration of mulching with drip irrigation can reduce the blue water footprint by 4.7%. Mulching may save 6.3–8.3 million m^3/y of water if an integrated drip irrigation system is applied [19]. An integrated modeling study has been conducted to explore water conflict between agriculture and ecosystems under environmental flow regulation, and the results recommended that dynamic and heterogeneous groundwater management policies should be implemented in water-scarce areas [20]. Limited and time-based water supply for agricultural production has been examined in the Zayandeh-Rud River Basin (one of the most water-scarce irrigation districts in Iran), and the results showed the significance and influence of a time-based water supply while planning an adaptive measure for irrigation systems [21].

Intensive multi-cropping systems, water pricing (cost-benefit analyses), plant sensor utilization, soil reclamation, and plant breeding are some practices that have been proven to effectively reduce the required amounts of water for irrigation. However, these approaches cannot provide an alternative source of water in different areas that do not already possess an abundance of water resources (e.g., arid and semi-arid areas). In general, the annual amount of water required for irrigation purposes has exceeded the available renewable amount of water, which has resulted in the occurrence of unsustainable groundwater exploitation [17]. In arid and semi-arid regions, the high temperatures and low precipitation makes it imperative to find alternative water resources for irrigation and soil reclamation to ultimately occupy desert areas and add new agricultural land [22–24].

3. An Overview of the Anticipated Variation in Vegetation and Precipitation

Based on the current information on the rapid increase in population, within the next decades, approximately one-third of the land surface on Earth should be exploited for cropland or pasture production. The global temperature is expected to increase, which will affect the global water cycle patterns and disturb natural ecosystems and human societies worldwide [25]. Moreover, freshwater resources will be directly affected by variations in precipitation patterns, which will negatively impact human livelihood and increase societal and economic pressure [25]. To combat this, the Paris Agreement set a goal to restrict mean global warming to below 2.0 °C and above preindustrial levels (1850–1900). Additionally, efforts to limit the increase in temperature up to 1.5 °C and Intended Nationally Determined Contributions (INDCs) have been submitted by several countries worldwide to achieve the main goals of the agreement [25]. A previous study [26] focused on the global vulnerabilities of agricultural land and food production to future water scarcity and the found that approximately 11% and 10% of the current crops and grasslands, respectively, could be vulnerable to water availability reduction, which may affect the productive capacity, particularly in the Middle East, Africa, China, Asia, and Europe. This tendency was also observed in lands that grow specific commodities (e.g., rice, maize, wheat, all fruit, all vegetables, and all pulses), and in this case, approximately 9–16% of the total land use could be classed as vulnerable. Furthermore, approximately 11% of the worldwide consumption of total grass biomass by the livestock sector, for the production of both milk and meat, takes place in regions that will be subject to reductions in water availability in the future [26].

A study by Zarei et al. forecast a reduction in vegetation cover (VC) in the eastern parts of the Chaharmahal-va-Bakhtiyari province, Iran, whereas an increase in VC (5–25%) was predicted in the western parts. The degradation of forests may lead to an increase in the total area of the grasslands. Generally, vegetation loss paves the way for grassland conversion to non-productive land cover types [27]. The total percentage of area that has been classified as vulnerable to water scarcity significantly differed from the other regions of cropland and pasture area as well as other commodities; for example, only 1% of land is vulnerable to water scarcity in Oceania, Canada, and Brazil, whereas the opposite trend exists in Africa and the Middle East (AME), Europe, and China. Vulnerable areas in Europe were found to be 20% and 16%, while these are 20% and 13% in China and 30% and 13% in AME for crop- and pastureland, respectively. The vulnerability of land used to produce wheat in both Europe and China is between 20% and 25%, whereas in AME it has reached 50%. Water scarcity may also affect animal production (e.g., meat and milk), especially in areas that use grazing as the main feeding method. This will ultimately impact productivity in Europe, AME, and China, in which cattle consume approximately 20% of the biomass that is grown in areas vulnerable to changes in water availability due to climate change [26]. Based on the model projections, it was reported that there will be a reduction in global agricultural areas between 2010 and 2050 and the shortfall in production of different commodities may lead to a knock-on effect on either current trade flow or regional economies [26]. In China, an increase of ~80.1% in the normalized difference vegetation index was observed for the period between 1982 and 2015, whereas degradation trends were found mainly in northeast China, North Xinjiang, and the Qinghai-Tibet Plateau. The future VC is predicted to be much better than that in the past period, excluding some areas, such as southeastern and northeastern parts in spring; however, vegetation degradation cannot be ignored in spring [28].

The SOS Mata Atlântica and INPE (2017) report found that the Atlantic Forest remnants (113 km^2) were less destroyed (9.3%) compared to the previous period. However, nine Brazilian states with Atlantic Forests have reached zero deforestation levels with less than 1 km^2 of deforestation, whereas some states continue to have high levels of deforestation [29]. Changes in precipitation patterns particularly in regions with extreme climate events (e.g., heavy rainfall or drought) are highly anticipated to exert considerable influence on East Asian countries that have warmer climate conditions. In East Asia, the precipitation in the spring and summer season (the main planting and growing season) have been affected by the relatively dryer fall and winter periods, which affects the management of water resources, agriculture strategy, the prevention of disaster, and other socioeconomic impacts [30]. Based on the previously mentioned information, water resources will be affected by future climatic changes together with the rapid increase in the world population, the development of the industrial sector, urbanization, and agricultural activities.

4. Innovations to Provide Secure Amounts of Water for Irrigation

4.1. Sahara Forest Project (SFP)

An article on the Jordan desert possibly being cultivated using a Greenhouse-Power Plant Hybrid was published in *Science* in January 2011 [31]. A combination of novel approaches were proposed to turn large areas of the desert into green areas for use in the commercial production of freshwater, food, electricity, and energy crops, making it the first large-scale project of its kind in Jordan. An agreement was signed between the Jordanian and Norwegian governments to begin work on the SFP. A Norwegian group specialized in environmental technology began construction near Aqaba on the Red Sea, in a 20-hectare demonstration center. It was anticipated to be operational at the beginning of 2015, as shown in Figure 3. The opening of the SFP Launch Station in Jordan was announced on 7 September 2017, in the presence of The Majesty King Abdullah II of Jordan and His Royal Highness Crown Prince Haakon of Norway [32].

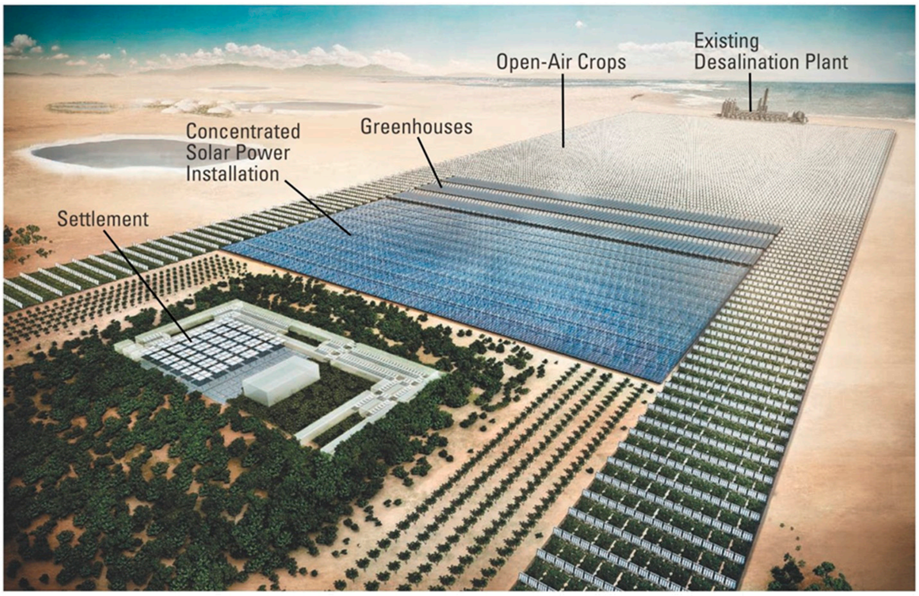


Figure 3. Photograph of the Sahara Forest Project (SFP), after (Daniel Clery, 2011) [31].

The principal functionality of the SFP is based on seawater evaporation, and the idea of bringing it to the desert area was developed by British inventor Charlie Paton. Pipes are used to direct the seawater into the trickles of a greenhouse over a grid structure, which covers the windward side of the greenhouse. When the natural breeze is bowed into the greenhouse through the grid, the water is evaporated, resulting in cool and moist conditions inside the greenhouse, ideal for crop growth. Another grid evaporator is fixed at the other end of the greenhouse that is fed by heated seawater (via black pipes on the roof of the greenhouse), which creates more moisture in the air as it leaves the growing area. Air with high humidity and high temperature then passes over a maze of vertical pipes (made of polyethylene) that have seawater passing through them, cooling the pipes. As a result, freshwater condensates on the pipes and trickles down into collectors. The resulting water can be used for either drinking or irrigation [31]. Solar power technologies (e.g., concentrated solar power and photovoltaics) are used for the electrical installations in the facility as well as the heat inside the SFP. The water is used for cleaning the solar installations. Pilot projects in Tenerife, Abu Dhabi, and Oman have also been built by Paton's Seawater Greenhouse Company since 1992 [31,32]. The SFP is summarized as follows [32]:

- The SFP is an integration of various environmental technologies, leading to restorative growth (e.g., revegetation and green job creation via the profitable production of freshwater, food, electricity, and biofuels).
- The SFP demonstrates the potential for restorative practices.
- The SFP uses resources available in abundance (e.g., saltwater, deserts, and CO_2) and turns them into the resources we need (e.g., water, food, and energy).
- The SFP is easily understandable and not too good to be true. It is an innovative solution based on logical perspectives (more holistic technologies to cope with the challenges of water security, energy, and food).
- The SFP is a distinctive integration of low-tech environmental solutions that relies on previously developed principles, resulting in highly desirable synergies.
- The SFP utilizes solar thermal technologies simultaneously with other technologies for saltwater evaporation and freshwater condensation to produce food and biomass without displacing existing agriculture or natural vegetation.
- The low-lying, arid, and sunny areas are considered best for the SFP facility to possess natural vegetation or agricultural activity.

- A total of 34,000 tons of vegetables were produced together with 155 GW/h of exported electricity. Moreover, the project employs over 800 people, and a single SFP facility has a solar power plant that can produce 50 MW and 50 ha of seawater greenhouses. It also captures about 8250 tons of CO_2.
- The SFP may create the opportunity for a wide variety of businesses to develop alongside it.
- The SFP may increase the potential of going green and being profitable, as the SFP provides ecosystem services.

Some progress reports from the SFP are as follows: 130,000 kg of vegetable crops are anticipated to be produced annually; it produces 10,000 L day^{-1} of fresh water; solar power is produced using photovoltaic panels; and it has a cultivation area of 3 hectares, comprising two greenhouses (1350 m^2), outdoor planting space (3200 m^2), and salt production ponds [32]. Regarding the future of the SFP in Jordan, the initial goal was to establish a launch station before expanding from small- to full-scale (20 hectares); therefore, the SFP is currently seeking investors to realize the goal of a full-scale station. A full-scale facility will be capable of producing vegetables of premium quality suitable for both domestic and international markets [32]. Additional information and news updates about the SFP can be found on the project website (https://www.saharaforestproject.com, accessed on 1 September 2022) [32].

4.2. Aquifer Recharge Approach

Managed aquifer recharge (MAR) is a promising groundwater engineering approach (also known as artificial recharge, water banking, and enhanced recharge). It is the intentional storage of water in aquifer reservoirs for environmental benefits; a process that has been utilized for over two thousand years (the initial prototype dates back to 221 B.C., China) [33]. Over 30 countries have successfully utilized MAR for water treatment and storage [34]. Soil aquifer treatment (SAT) is an approach in which wastewater effluent is recharged through intermittent percolation in infiltration basins, and agricultural MAR (Ag-MAR) is the off-season flooding of agricultural lands. An agricultural SAT (Ag-SAT) was proposed to integrate both the Ag-MAR and SAT, owing to the limited availability of land resources for SAT and the increased amounts of available treated wastewater. Additionally, the treated wastewater could potentially provide nutrients to agricultural fields during flood cycles [5].

The continuous extraction of natural groundwater depletes this resource, which may lead to irreversible damage [5,33]. Preserving water in an underground aquifer has more value than surface water recharge because it has the advantages of avoiding evaporation losses, does not require a large area, sediment accumulation is limited, and there is less possibility of structural failure and contamination. Figure 4 shows a schematic diagram of the different types of MAR techniques [33].

The MAR approach has several advantages for water resource management (e.g., supports high water demand and the management of water supply and demand during temporal mismatching, improves water quality, and protects against evaporation losses and algal blooms, among others). MAR encompasses various types of water sources (e.g., river water (53.4%), rainwater, storm water, treated effluent (17%), desalinated seawater, and water from other aquifers) [33]. The global population relies on groundwater for over 30% and 40% of drinking and agricultural water, respectively [5].

The annual amount of water required for irrigation has exceeded the available amounts of water, which has resulted in the occurrence of unsustainable groundwater exploitation. It has been mentioned that the water table declined rapidly from 10 m to 40 m from the 1970s to the early 2010s. The dependence of industries and municipalities on groundwater is an additional pressure that rapidly decreases the water table level; thus, to ensure aquifer water sustainability, the overexploitation of groundwater must stop [17]. The overexploitation of deep groundwater is a prominent activity in the North China Plain and may affect the sustainable utilization of water resources in this area. The MAR implementation rate has increased annually by 5% in the past few decades [33]. MAR is classified into five categories based on recharge and storage as follows: (a) spreading methods; (b) in-channel modifications; (c) recharge by well, shaft, and boreholes; (d) induced bank filtration; and (e) runoff harvesting. The key process of MAR implementation involves four stages, including (a) planning, (b) investigation, (c) design, and (d) construction and operation. Moreover, to ensure the successful performance of the MAR application nine major elements should be considered as follows: (1) recharge water sources, (2) recharge method, (3) recharge site, (4) water recovery, (5) ultimate uses of recovered water, (6) regulations, (7) hydrogeology, (8) water quality control, and (9) monitoring and maintenance [33].

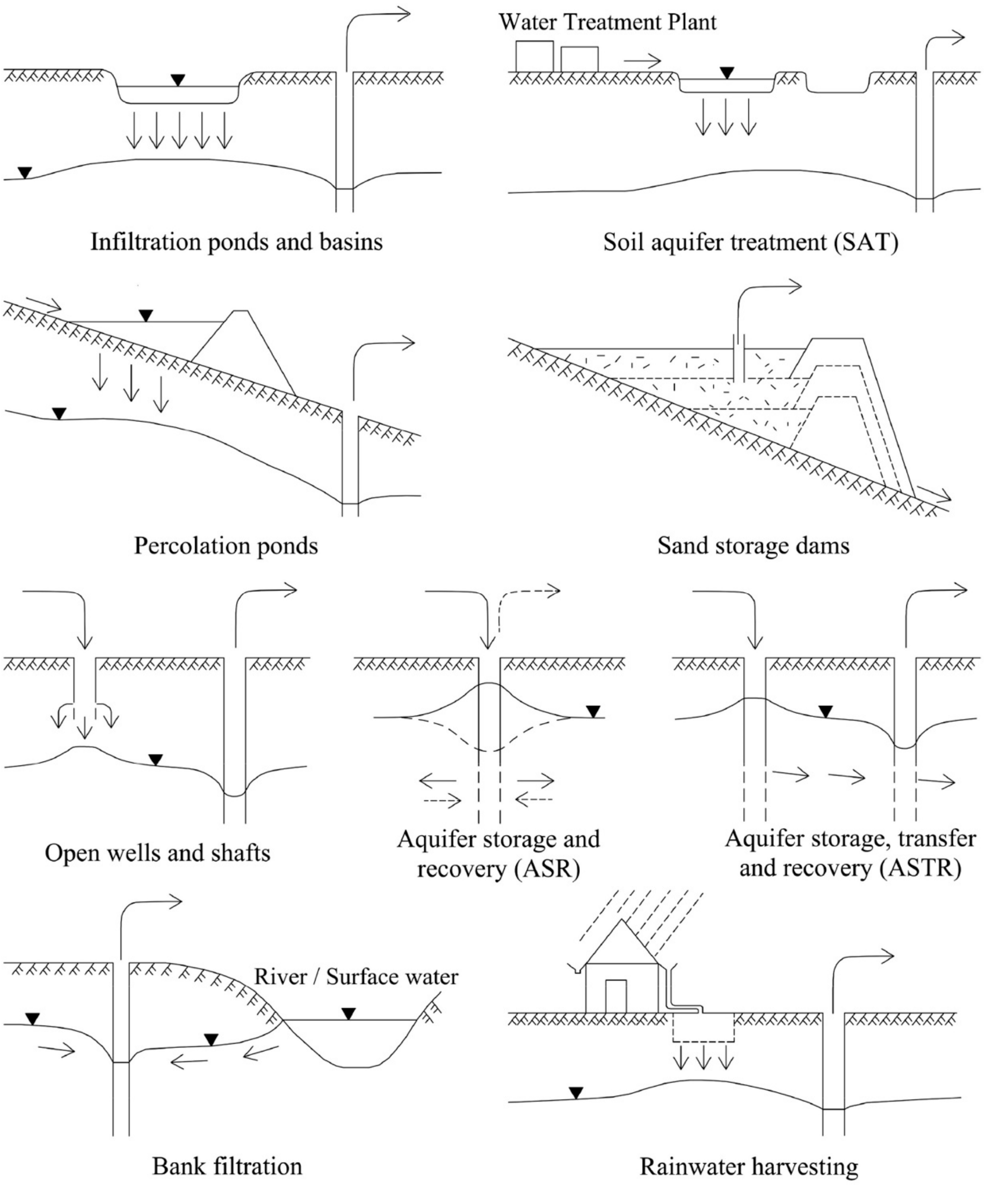


Figure 4. A schematic diagram shows the different types of MAR techniques (H. Zhang et al.) [33].

Globally, approximately 1104 MAR sites have been registered for general use in the following sequence: domestic (59.9%) > agricultural (24.8%) > ecological and environmental protection (9%) > industrial (3.9%). The MAR approach can also be utilized for specific fields of application, such as water resources adjustment, utilization of geothermal resources, water quality improvement, and ecological and environmental protection [33]. The persistent trace organic chemicals that cannot be bio-transformed during wastewater treatment can be removed in significant amounts by subsurface microbial communities or via adsorption through aquifer media during the intentional recharge of water [35].

The sustainable operation of MAR schemes may face several obstacles and challenges such as (a) clogging, (b) aquifer damage concerns, (c) MAR seepage calculation, and (d) water purification mechanism of the managed aquifer recharge [33]. In northern Australia, the MAR budget was estimated to be approximately \$0.04 to \$0.36/m^3 for 0.6–5 Mm^3/y capacity, and a budget of 1 Mm^3/y was reported for schemes such as recharge release, infiltration basins, recharge weirs, aquifer storage transfer, aquifer storage and recovery, and seawater intrusion barriers. The lowest budget was found for infiltration type and well injection. The combination of MAR schemes can facilitate the use of groundwater and surface water to enhance agricultural water management. The large-scale storage of water may be achieved by constructing dams, which result in a reduction in levelized costs for an annual yield of 55–1248 Mm^3 by \$0.03 to \$0.18/m^3. In addition, it was reported that MAR is suitable for low-relief areas as well as mosaic irrigation [34].

The relationship between land subsidence (the sinking of the ground) and groundwater extraction, in addition to the occurrence of ground uplift phenomena due to the heterogeneities and distribution of extraction bores in subsurface geology, may include a persistent linear feature that is often neglected in the regional hydrogeological models. The inelastic compaction of aquifers may occur with long-term irrecoverable subsidence. Approximately, 3–6 mm/yr subsidence has been observed in Perth since the 1970s–1990s [36]. The continuous abstraction of groundwater eventually reduces water table levels, causing groundwater salinization, particularly in coastal aquifers [5]. In the countries of the Gulf Cooperation Council (GCC), groundwater discharge and recharge account for 27.8 and 5.3 billion m^3, respectively, indicating a significant imbalance in reducing groundwater levels [37]. A wide variety of contaminants from anthropogenic activities have reached the groundwater and caused pollution, deteriorating the water quality (e.g., nitrate pollution, particularly in agricultural regions). This is mainly due to the severe application of fertilizers rich in nitrogen, limited denitrification, and the inappropriate disposal of waste (human and animal) [5]. Accordingly, the MAR is considered as an appropriate approach for preserving water for irrigation, however, the previously mentioned issues should be considered before exploiting this source for irrigation.

4.3. Treatment of Marginal Water Using a Magnetic Field

Exposing irrigation water to a magnetic field method (MFM) attracts special attention when compared with other chemical and physical treatment approaches for marginal water, owing to its safety, simplicity, and ecological purity [38]. Figure 5 shows a photograph of an operational MFM machine installed in the field [39,40]. The MFM reduces the hydration of salt ions and other impurities, accelerates coagulation, and improves salt solubility [41]. The MFM has also been investigated in several regions, such as Australia, Russia, China, Israel, and Japan [39]. The influence of the magnetic field on irrigation water increases the number of crystallization centers and changes the free gas content, which results in improved water quality for irrigation. The flow rate and chemical parameters of water (e.g., hydrogenous ion concentrations at $pH > 7.2$ and a carbonated water hardness of >50 mg L^{-1}) are considered the most important factors for effective magnetic treatment [38].

Studies that were conducted using magnetic field application (MFA) during irrigation demonstrated that it enhanced plant growth, increased the availability of soil nutrients, positively impacted cation uptake capacity, reduced the immobility uptake of plant nutrients, leaching soil salts, increased yield productivity (e.g., tomato, eggplant, and cowpea), and the deleterious effect of agricultural drainage water when reused for vegetable crops irrigation was reduced [42]. Magnetic field application plays an important role for marginal water and has a noticeable impact on plant growth, such as barley (*Hordeum vulgare* L.), by altering the magnetic characteristics of plants, affecting the nutrient uptake ability and abundance in tissues, and improving photosynthetic machinery, which leads to efficient growth and germination.

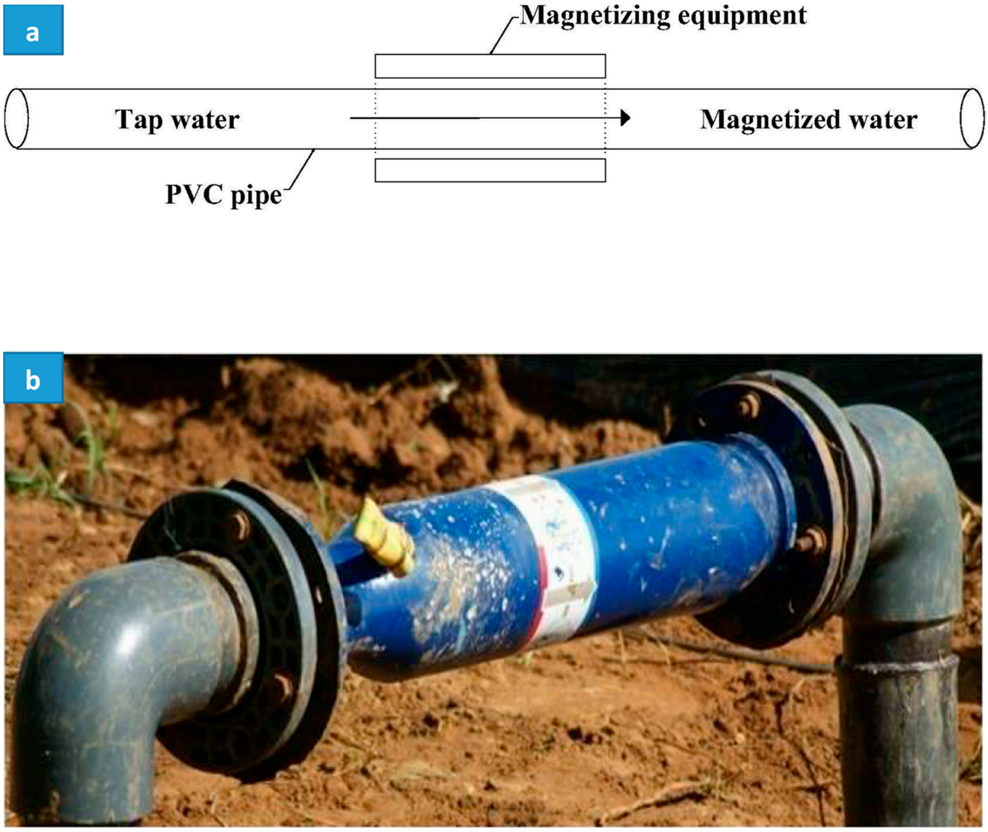


Figure 5. A schematic diagram (**a**) and photograph of the magnetic treatment device (**b**) (Y. Wang et al.; H. Taimourya et al.) [39,40].

An enhanced growth response of several plants has been reported, for example, chickpea (*Cicer arietinum*), sunflower (*Helianthus annuus*), rice (*Oryza sativa*) [43], and cucumber [44]. The germination of wheat and growth and yield of fruit were also increased after the pre-treatment of seeds (5–15 min) with external MF (5–15 mT) [43]. The static magnetic field improved the α-amylase activity in brown rice by 15.2% [45]. The MFA also has the ability to reduce energy consumption during water electrolysis [46]. Moreover, it was mentioned that using irrigation water treated with a magnetic field was highly beneficial for soils containing high sodium concentrations [38].

Using magnetic field via iron fillings at a rate of 150 kg ha^{-1} resulted in the high tomato yield and economic efficiency improved by using freshwater (100%) with the exposure to magnetic field. Moreover, it was observed that when using a mixture (75% freshwater + 25% drainage water) with the magnetic field application, tomato yield productivity was equal to that obtained solely from freshwater (control). This perspective may be valid in the case of a slight freshwater shortage. However, in the case of a severe shortage of irrigation water (freshwater), a mixture of 50% freshwater + 50% drainage water or 25% fresh water +75% drainage water with magnetic field application is recommended; this will result in a <10% reduction in relative yields compared to the control experiment, which is considered acceptable by tomato producers [42]. Treating irrigation water with a magnetic field resulted in enhanced strawberry production and quality [39]. Although a magnetic field was applied at a low frequency, it was capable of decreasing the total dissolved solids and electrical conductivity [41]. The N utilization rate was reduced for ammonium sulfate when magnetically irrigated water interacted with N-forms, whereas an improved utilization rate for ammonium nitrate was observed [47]. It was recommended that adding nutrients via fertigation after MFA ensures a positive impact on both soil and water properties, and the tuber engineering parameters increased potato productivity by

40.5% compared with normal water [48]. Irrigation using MFA was also capable of reducing the soil salinity (e.g., EC and SAR) and soluble cations and anions that exist in the soil root zone. Moreover, moisture content, soil field capacity, and available water increased in sandy soil after MFA application [49]. It was mentioned that the efficiency of MFA differed based on the type of irrigation and plants. The plant yield and water productivity increased for a every kilogram of fresh or dry produce per liter of water used, and the MFA improved celery yield by 12% and 23% using recycled and saline water (3000 ppm), respectively [50].

4.4. Desalination and Wastewater Treatment for Marginal Water Reuse

Desalination and treatment technologies are used to provide unconventional water supply for irrigation purposes. In the 1960s, the first large-scale desalination plant was constructed. Globally, some 20,000 facilities are performing the desalination process, and over 300 million people are dependent on desalinated water [6]. In the countries of the GCC, approximately 5.75 billion m^3 of desalinated water is produced annually from 439 desalination plants, whereas 300 wastewater treatment plants treat approximately 73% of 4.0 billion m^3 of wastewater collected, of which only 39% is utilized by the agriculture sector, and the remaining amounts are discharged directly into the sea [37].

Desalination technologies include several processes that may be classified based on the type of energy used, namely thermal and none-thermal desalination (e.g., reverse osmosis, crystallization, and electrodialysis), as shown in Figure 6a [51], and the desalination technologies themselves are classified into two categories: water separation and salt separation (Figure 6b) [51]. Wastewater treatment may be classified into primary, secondary, and tertiary schemes, as shown in Figure 7 [52,53].

The reuse of desalinated water for irrigation is highly advantageous and provides water security and availability; however, the water quality standards, production capacity of the desalination plants, high price affecting profitable crop options, high-energy consumption, water shortage due to technical problems, no seasonal variation in water production, and socio-political aspects are the main obstacles preventing large-scale application [6]. For reclaimed wastewater, several benefits were reported, including the provision of a considerable amount of water, which decreases the water crisis burden [54], provides economic support [8], decreases the stress on water aquifers [8,55], and reduces the budget dedicated for irrigation [8]. Some other benefits of reclaimed water include decentralized systems that can be comparatively cost-effective under certain circumstances [56], less energy is consumed [3], environmental security is promoted [3,57], and it can be used for building construction [58] and the industrial sector [59]. However, the obstacles of reclaimed water use are summarized as follows:

(a) reclaimed water has different properties to tap water [60].
(b) low amount of treated water compared with other sources [60]; in addition, there are some environmental concerns [37].
(c) the imbalance between demand and supply [60].
(d) construction of a water reservoir is required to store the reclaimed water after it is discharged from a wastewater treatment plant (WWTP) [60,61].
(e) WWTPs do not have the capacity to treat all amounts of the produced wastewater [61].
(f) the nutrients in treated wastewater are not sufficient to provide significant doses to plants [62].
(g) the public acceptance of the wastewater treatment strategy and building social trust are important factors that must be addressed [55].
(h) the high costs of testing and process validation associated with the guaranteed removal of pollutants and pathogens from feed water to the minimum permissible levels [63].
(i) the financial challenges for routine operations [61].
(j) most of the advanced wastewater treatment plants are located in primary cities, whereas small cities usually rely on traditional approaches for wastewater treatment [58].

(k) negative impact on soil, plants, and human beings, in some cases [3,8].
(l) The use of treated water is inappropriate for some sensitive irrigation systems [8].
(m) there are still no comprehensive global regulations considering the emerging contaminants that remain in reclaimed water, such as PPCPs, endocrine disruptors, and antibiotic resistance determinants [8].
(n) coordination among governing agencies [64].
(o) the lack of knowledge about the terms and conditions of reclaimed water use as an alternative water resource [56].
(p) reclaimed water is rich in nutrients and can be utilized as fertilizer to grow crops or for landscape production; however, an excess of these nutrients may cause several issues in certain circumstances, such as excessive vegetative growth, delayed or uneven maturity, and reduced crop quality [3].
(q) the existence of micropollutants in wastewater at low concentrations (e.g., pesticides, diclofenac, ibuprofen, endocrine disrupters, carbamazepine, and caffeine) is considered an enormous challenge in selecting the ideal wastewater treatment technology [9].

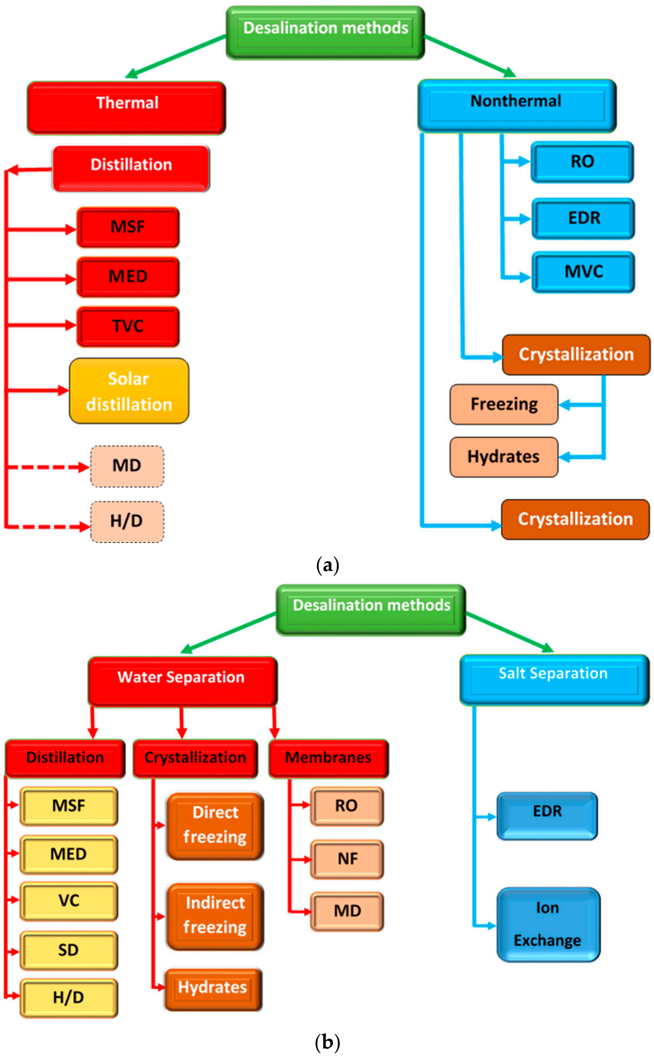


Figure 6. (**a**) Desalination methods according to the type of energy utilized (Belessiotis et al.) [51]. "Thermal conventional desalination methods are presented in red and conventional desalination methods are fired by electricity in Blue. Brown color refers to methods that were applied but found no wide application" (Belessiotis et al.) [51]. (**b**) Classification of desalination approaches according to the separation mode (water or salts) (Belessiotis et al.) [51].

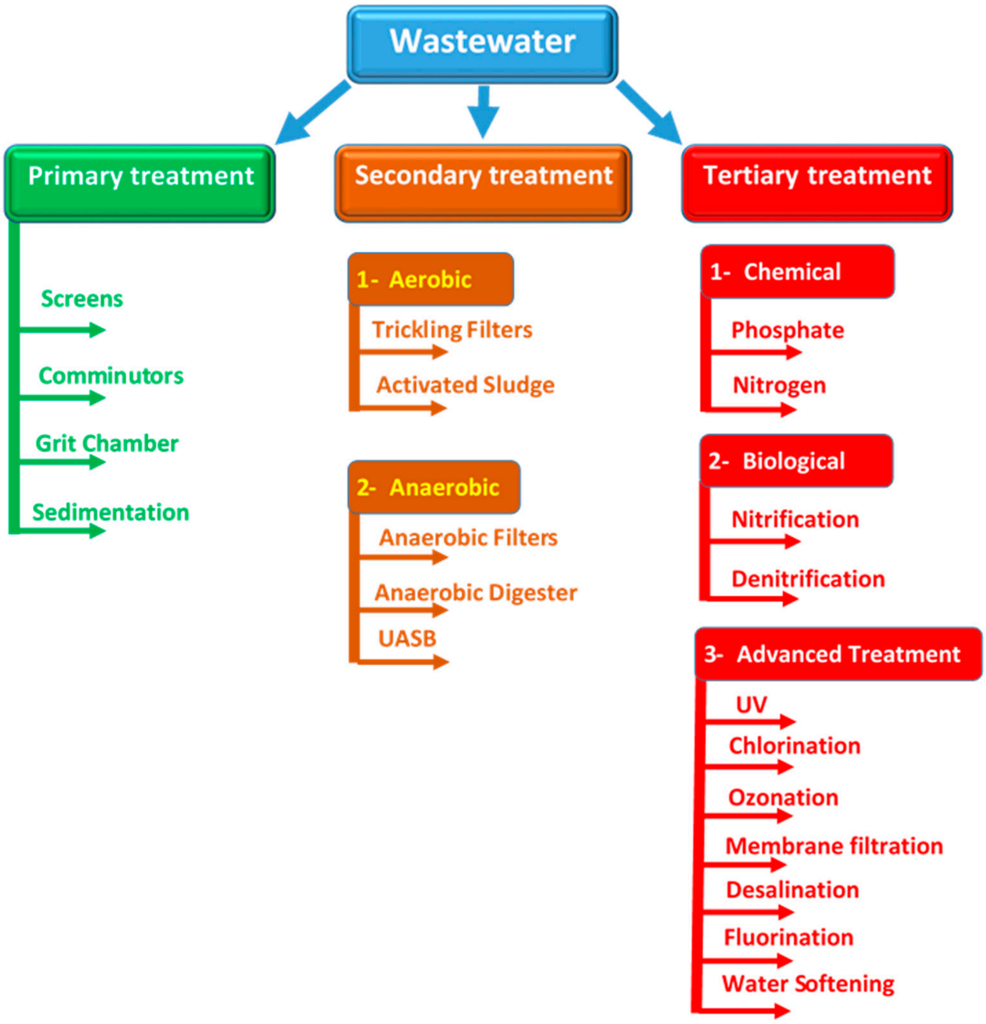


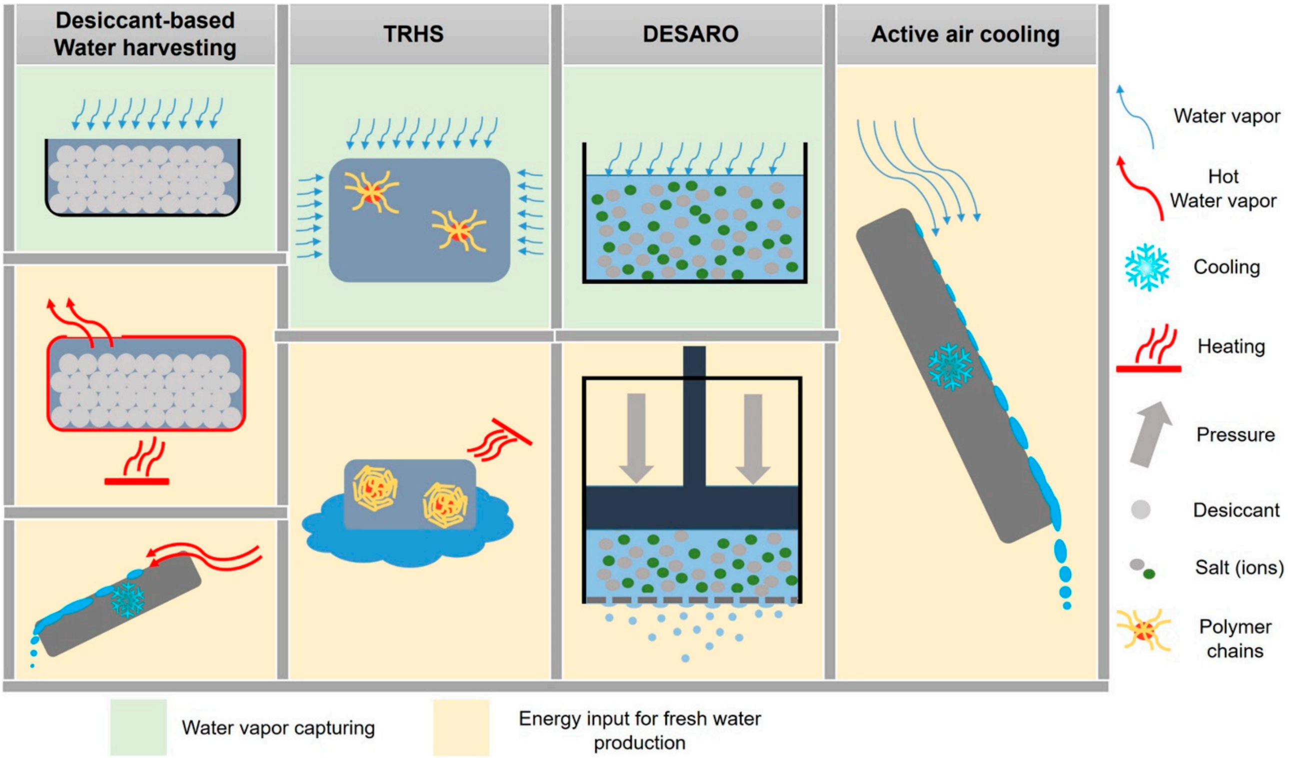
Figure 7. Wastewater treatment scheme (Sharma et al., 2019) [52].

4.5. Extraction of Water from the Air

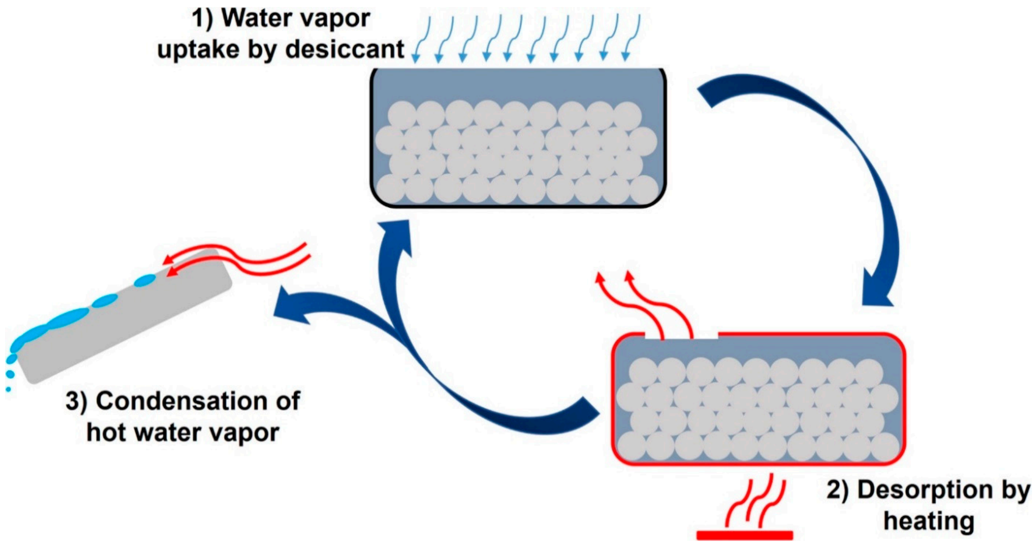
The extraction of water from the atmosphere (the condensation of hot humid air on cool surfaces) is a well-known approach that was used in ancient times (e.g., Feodosia city, where the water supply was obtained using crushed-stone mounds in the form of a pyramid) [65]. The water harvesting technologies include dew harvesting, fog collection, active air cooling, and desiccant-based water harvesting. Figure 8 shows the desiccant-based water harvesting process [66]. The extraction of water from the atmospheric air (EWAA) may be considered an alternative water supply, as it produces approximately 10,000–30,000 m^3 of pure water from one square kilometer in most regions worldwide [67].

The EWAA method is based on converting air humidity into water using a three-stage process, namely absorption, desorption, and condensation, as shown in Figure 8 [66,67]. First, the humidity is absorbed using a solid desiccant, then the water-to-vapor desorption is applied at a moderate heat (65–85 °C), and finally, the passive condenser, connected to a heat pump, is used for condensation. The integration of these three stages makes it possible to produce water at low energy (100–150 kcal/L) [67], whereas another study found that the EWAA method is energy-demanding (approximately 50% of the total cost) [66]. The EWAA method has the advantage that no infrastructure is required [67]; however, it does not compete with the desalination of seawater, wastewater reuse, and freshwater [66]. The EWAA method can be used at an ambient temperature (5–115 °C) with a relative humidity of ≥20%; however, it achieves maximal capacity at a relative humidity of 60%. The EWAA method may be able to provide water in dry regions (e.g., southern

Mediterranean countries), regions suffering from water pollution (e.g., tropical countries), drought-affected and adverse climate change areas, and inland regions [68,69]. The EWAA method is also considered a viable option for reducing long-distance transportation cost from a socioeconomic perspective and/or for areas with no local fresh water resources [66].



(**a**)



(**b**)

Figure 8. (**a**) The four main atmospheric water harvesting processes (Peeters et al.) [66]. (**b**) The desiccant-based water harvesting process (Peeters et al.) [66].

The use of thermo-responsive polymers shows excellent performance, as their material configurations change from hydrophilic to hydrophobic upon heating; thus, they expulse absorbed water directly into liquid form [66]. It was reported that the utilization of nanomaterials in the heat exchange unit also resulted in effective water extraction, specifically at 20 °C, and a relative humidity of <5% [65]. The results of using tubular solar stills (TSS) to extract water from atmospheric air showed that the minimum production was 230 mL/m^2/d for natural air circulation with 12.2% thermal efficiency, whereas the maximum water production was 467 mL/m^2/d for a 4 m/s air speed with 25% thermal efficiency. In this approach, the estimated cost was USD 0.4/L and USD 0.2/L for natural air circulation and 4 m/s air speed, respectively. TSS technology is suitable for the regions that are located in deserts, owing to its capability of extracting water from a low humidity atmosphere, and has the advantage of direct application without any infrastructure required [70]. In addition, a recent study showed that the novel composite material, HKUST-1/LiCl, has the best potential for EWAA in the presence of natural sunlight [71]. Several studies have focused on EWAA using various approaches [68,69,72–74]. Additionally, several reviews have been published focusing on EWAA [75–78]. However, based on our literature survey, pilot-scale applications of the EWAA method for irrigation do not exist. This may be due to the large amount of water required for irrigation purposes.

4.6. Electro-Agric Technology (E-AT)

Recently, the principles of electro-agric technology (E-AT) have been introduced in the agricultural sector as a trial to overcome the water crisis through marginal water reuse [22]. The E-AT has five main components, including water, soil, organic matter, plants, and others that will be discussed from a specific perspective, as shown in Figure 9. Here, we focus on the first domain of electro-agric technology: water management from different perspectives. Electro-agric technology proposes that the current existing approaches dedicated to desalination and wastewater treatments, including reverse osmosis, nanofiltration (NF), thermal desalination, and adsorption/desorption, may not be appropriate for irrigation, because these technologies do not possess the capability of removing specific ions that are the main problem for irrigation (e.g., Na^+, B, and Cl^-). These technologies are based on the separation and purification of salts in water as a bulk quantity that increases total costs. In addition, most of these technologies are based on the separation of water from brine water or wastewater. Electro-agric technology proposes that electrodialysis technology is suitable for small- and large-scale agricultural applications; however, the present design is still not suitable for large-scale agricultural applications, owing to its civil and environmental engineering design that ensures human welfare [23].

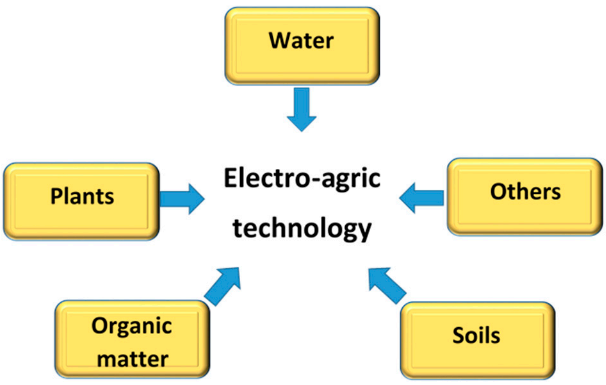


Figure 9. A schematic diagram shows the principles and basics of electro-agric technology (E-AT) [22].

Electrodialysis technology performance is based on the separation of ions from saltwater or wastewater during desalination, which allows the treatment of large amounts of water required for irrigation and other purposes [79–81]. Electro-agric technology proposes a new generation of electrodialysis (NGE) technology to fulfill the agricultural necessities that are of interest to the electro-agric group at the Desert Research Center (DRC), Egypt. NGE technology can be introduced using the following specific procedures [22]:

(a) Accelerating the migration of ions inside aqueous solutions
(b) Manufacturing novel designs of cationic and anionic exchange membranes to improve the separation selectivity of specific ions, such as Na^+, Cl^-, and B.
(c) Introducing novel electrodes and membranes to enable the large-scale production of water suitable for agricultural use.

The electrodialysis brine solution that discharges during the operation will be treated with E-AT, using a new method to avoid further problems that may eventually affect the environment and surrounding ecosystems. Generally, the outlet brine solution from wastewater or saltwater is handled through (a) precipitation in its solid form, (b) recovering solids using electrolysis, and (c) discharging it into the sea. However, E-AT proposes the handling of brine solution using specific electrolysis and electrodialysis techniques producing bases (e.g., NaOH) and acids (e.g., HCl) that may be an economic booster for the industrial sector, ultimately reducing total costs. Electro-agric technology mainly emphasizes the optimization and screening of the prototypes, trials, pilot, and large-scale applications using mathematics modeling (e.g., the Taguchi approach) to ensure precise results in a short period [22]. Moreover, economic evaluation and public acceptance will be considered to ensure the wide distribution of this technology in the Middle East and North African countries (arid and semi-arid regions). Electro-agric technology also proposes the mandatory treatment of industrial wastewater within the factories to decrease the burden of wastewater reuse that is currently accepted worldwide [82]. In addition, E-AT proposes the integration of water, soil, organic matter, plants, and other factors to ensure the sustainability of such processes. The E-AT project is still considered to be under development by the electro-agric group at the DRC, Egypt [22].

4.7. Toshka Project (TP)

The Egyptian government established the Toshka Project (TP), which is an integral part of a much larger mega project, the Southern Valley Development Project (SVDP). The TP was announced on 9 January 1997 and was ground breaking in January 1998 [83,84]. The Toshka Region is located south of Cairo (~965 km) and southwest of the Aswan governorate (~225 km). The aim of the TP is to develop Upper Egypt by doubling the amount of cultivated land in the Toshka, East El-O-Wee-Nat, and New Valley Oases and to excavate a canal that is capable of transporting large amounts of water every year from Lake Nasser to the Toshka Depression, southwest of Aswan [84]. Approximately 600 thousand feddans (~252,000 hectares) may be cultivated in this area, and this number is due to be increased in the future to ~1 million feddans (~420,000 hectares) irrigated using surface and groundwater [83]. Figure 10 shows the location of the TP [85,86]. The TP will ultimately create a new valley to the Nile River in the western desert of Egypt. In this region, Toshka City is considered a new metropolitan city that will be able sustain a population of approximately five million people in the future. This area has a natural depression, known as the Toshka Depression, that is characterized by an average diameter of 22 km and a capacity of (120 billion m^3) [87]. Toshka Bay is an off shoot of Lake Nasser in the direction of Toshka. When the water of Lake Nasser exceeds its storage level of 620 ft (~187 m) [84,87], the water is discharged into a man-made spillway canal (22 km long connection), which is used as a safety valve for Lake Nasser, upstream of the High Dam, and is connected to Toshka Bay via the Toshka Depression [84,86,87]. The Aswan High Dam is the largest constructed freshwater reservoir in the world [88].

The TP involves the Toshka Canal (TC), which is considered the "heart and soul" of the project. This canal is used for transporting the excess water of Lake Nasser after it is pumped by an enormous pumping station (capable of elevating the water up to 54 m) [83,84]. The pumped water flows through the TC and is used for irrigation and the reclamation of new land in the western desert of Egypt ~520,231 to 534,000 acres (210,530 to 216,102.1 hectares) [84,87]. The SVDP is not only an irrigation or agricultural project but is considered a multifaceted, multiphase development project. It includes land reclamation and horizontal expansion projects in the southern region of Egypt and is a national, integrated, and massive development. Through the SVDP it will be possible to re-organize the Egyptian map from different perspectives, such as the habitation, economic, and demographic [83,84].

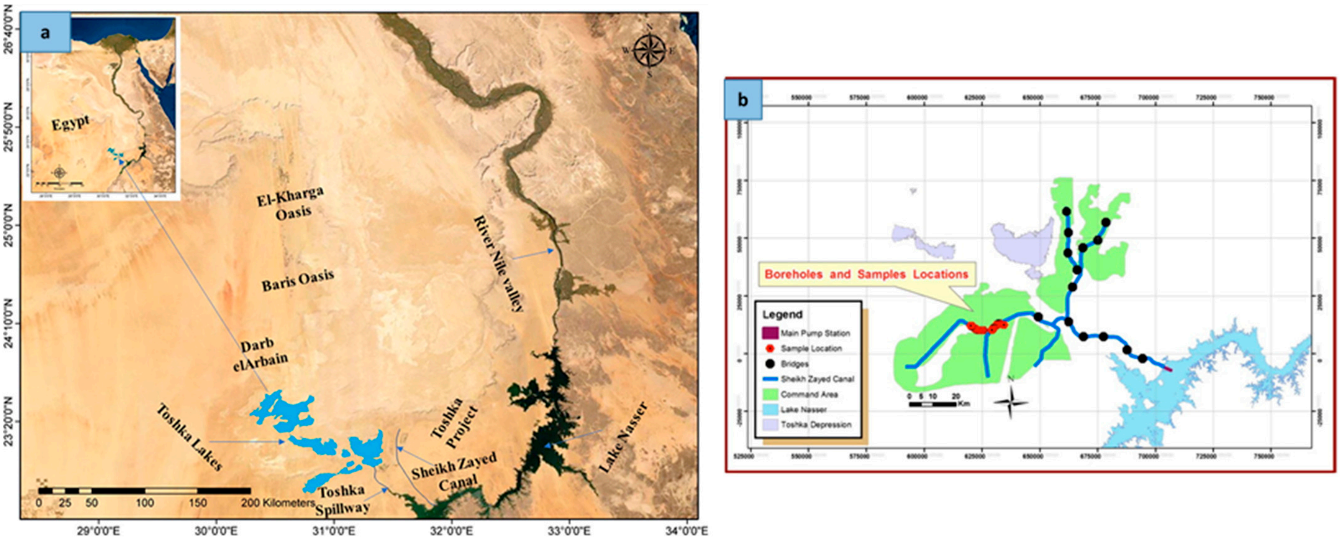


Figure 10. Egypt, Western Egyptian Desert, Toshka Lakes, and other features (**a**), and the location of the Toshka Project (**b**) (Abd Ellah and Sparavigna; Labib and Nashed) [85,86].

The infrastructure of TP involves the Mubarak Pumping Station (MPS), the main pumping station; the TC; water production wells; artificial charging; and breakers for sand and wind storms. The MPS was constructed on the left bank (west) of Lake Nasser (north of Toshka Bay), and it pumps 25 × 10^6 m^3/day of water to the main feeding canal [83,84]. The MPS site excavation began in June 1998. The multistage MPS is designed to provide a maximum static head of ~54 m, while the minimum static head is 19 m, making it one of the largest pumping stations in the world. The MPS is capable of working even when the water level in Lake Nasser is at its lowest level of storage (147 m) [83,84,87]. In November and December every year, the lake level reaches its highest level (182 m), then decreases gradually until July [87,88]. The MPS is an integral part New Valley Development Project, the objective of which is to establish an agro-industrial development of approximately 988,000 acres (~399,829.4 hectare) in the adjacent area [84]. The wind and sandstorm breakers are comprised of kaya and poinciana trees, grown in two rows on each side of the main canal, in addition to the four branches (approximately 104 km of trees were planted prior to 2004) to protect the main canal from sand- and wind-storms that occur in this region throughout the year [84].

The TP presents several advantages that can be summarized as follows [83,84]:

1. Overcoming the problems that arise from annual population increases in Egypt by adding new agricultural areas, creating new communities, increasing national income, and creating job opportunities.
2. Increasing the amount of cultivated land in Upper Egypt (doubling the area).
3. Utilizing water stored in Lake Nasser for agricultural development.
4. Offering space for navigation and waterway transportation.
5. Facilitating power generation projects.
6. Developing and promoting tourism, fishing, and recreational activities, among other things.
7. May lead to new archeological discoveries in the future.
8. Decreasing the amount of silt accumulating in Lake Nasser that formed after the construction of the Aswan High Dam in the 1960s and reducing the negative impact on both the capacity of the lake and the stability of the High Dam.
9. A population of five million people could live in Toshka City, which may decrease the burden in the crowded old valley.

10. Enhancing the pharmaceutical and fish-processing industries by increasing botanical and animal resources.
11. Attracting wild birds and other animals by developing a suitable environment within the area of the new project.
12. Developing solar and wind energy as clean, renewable electrical power in this area.

5. Conclusions

The global water crisis intensifies the stress on the available freshwater resources, which creates an enormous challenge for providing an adequate amount of water for irrigation purposes. This is a problem for the agricultural sector, which consumes the most water (70–80%) compared to other sectors, such as industry, and to domestic use. This study summarized the recent innovations that have been introduced to overcome the global water crisis with an emphasis on irrigation. Seven approaches were summarized: (1) the Sahara Forest project, (2) aquifer recharge approach, (3) the treatment of marginal water using a magnetic field, (4) desalination and wastewater treatment for marginal water reuse, (5) the extraction of water from the air, (6) electro-agric technology, and (7) the Toshka Project. The Sahara Forest project has been implemented in Aqaba, Jordan, and is expected to increase in size and capacity within the next few years. The aquifer recharge approach has an advantage over surface water storage; however, clogging, aquifer damage, and the seepage calculation of MAR are the main obstacles of this approach. The application of a magnetic field for treating marginal water is a feasible approach with significant results in plant productivity. This approach has garnered special attention when compared with other chemical and physical treatment approaches because of its safety, simplicity, and ecological purity. The desalination and wastewater treatment of marginal water for reuse purposes may provide an unconventional water supply; these approaches are accepted worldwide. The extraction of water from the air may be an advantage for inland countries that are located far from a traditional water supply; however, to date, no research has been reported for its large-scale application in irrigation because of the large amounts of water supply required by the agricultural sector. Electro-agric technology is a novel approach and has five main components, including water, soil, organic matter, and plants, among others. E-AT is still being researched and requires verification to ensure the feasibility of its principles and foundations for pilot-scale applications in greenhouses. Lastly, the Toshka Project is an amazing idea that utilizes the water stored in the High Dam in Lake Nasser to create new communities and improve the national economy, in addition to several other advantages. We suggest the establishment of small-scale projects using these approaches in each region to allow for a good comparison of main outputs, thus enabling the most appropriate and beneficial approach for agricultural development to be chosen.

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Data Availability Statement: The datasets used and/or analyzed during the current study are available from the corresponding author on reasonable request.

Conflicts of Interest: The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Table of Acronyms and Abbreviations

SFP	Sahara Forest Project
E-AT	Electro-agric technology
WEA	Water extraction from air
AR	Aquifer recharge
MF	Magnetic field
DWT	Desalination and wastewater treatment
VC	Vegetation cover
AME	Africa and the Middle East
NGE	New generation of electrodialysis
MAR	Managed aquifer recharge
SAT	Soil aquifer treatment
Ag-MAR	Agricultural MAR
Ag-SAT	The agricultural SAT
MFM	Magnetic field method
MFA	Magnetic field application
WWTP	Wastewater treatment plants
EWAA	The extraction of water from the atmospheric air
TSS	Tubular solar stills
TP	Toshka Project
TC	Toshka Canal
MPS	Mubarak pumping station
GCC	The Gulf Cooperation Council
SVDP	The Southern Valley Development Project

References

1. Yin, L.; Tao, F.; Chen, Y.; Wang, Y. Reducing agriculture irrigation water consumption through reshaping cropping systems across China. *Agric. For. Meteorol.* **2022**, *312*, 108707. [CrossRef]
2. Murray, S.; Foster, P.; Prentice, I. Future global water resources with respect to climate change and water withdrawals as estimated by a dynamic global vegetation model. *J. Hydrol.* **2012**, *448*, 14–29. [CrossRef]
3. Ricart, S.; Rico, A.M. Assessing technical and social driving factors of water reuse in agriculture: A review on risks, regulation and the yuck factor. *Agric. Water Manag.* **2019**, *217*, 426–439. [CrossRef]
4. Bwambale, E.; Abagale, F.K.; Anornu, G.K. Smart irrigation monitoring and control strategies for improving water use efficiency in precision agriculture: A review. *Agric. Water Manag.* **2022**, *260*, 107324. [CrossRef]
5. Grinshpan, M.; Furman, A.; Dahlke, H.E.; Raveh, E.; Weisbrod, N. From managed aquifer recharge to soil aquifer treatment on agricultural soils: Concepts and challenges. *Agric. Water Manag.* **2021**, *255*, 106991. [CrossRef]
6. Villar-Navascués, R.; Ricart, S.; Gil-Guirado, S.; Rico-Amorós, A.M.; Arahuetes, A. Why (Not) Desalination? Exploring Driving Factors from Irrigation Communities' Perception in South-East Spain. *Water* **2020**, *12*, 2408. [CrossRef]
7. Wang, H.; Feng, D.; Zhang, A.; Zheng, C.; Li, K.; Ning, S.; Zhang, J.; Sun, C. Effects of saline water mulched drip irrigation on cotton yield and soil quality in the North China Plain. *Agric. Water Manag.* **2022**, *262*, 107405. [CrossRef]
8. Sapkota, A.R. Water reuse, food production and public health: Adopting transdisciplinary, systems-based approaches to achieve water and food security in a changing climate. *Environ. Res.* **2019**, *171*, 576–580. [CrossRef]
9. Faria, D.; Oliveira, A.; Baeza, J.A.; de Miera, B.S.; Calvo, L.; Gilarranz, M.A.; Naval, L. Sewage treatment using Aqueous Phase Reforming for reuse purpose. *J. Water Process. Eng.* **2020**, *37*, 101413. [CrossRef]
10. Otter, P.; Hertel, S.; Ansari, J.; Lara, E.; Cano, R.; Arias, C.; Gregersen, P.; Grischek, T.; Benz, F.; Goldmaier, A.; et al. Disinfection for decentralized wastewater reuse in rural areas through wetlands and solar driven onsite chlorination. *Sci. Total Environ.* **2020**, *721*, 137595. [CrossRef]
11. Coelho, R.D.; de Almeida, A.N.; Costa, J.D.O.; Pereira, D.J.D.S. Mobile drip irrigation (MDI): Clogging of high flow emitters caused by dragging of driplines on the ground and by solid particles in the irrigation water. *Agric. Water Manag.* **2022**, *263*, 107454. [CrossRef]
12. Al-Agele, H.A.; Jashami, H.; Higgins, C.W. Evaluation of novel ultrasonic sensor actuated nozzle in center pivot irrigation systems. *Agric. Water Manag.* **2022**, *262*, 107436. [CrossRef]
13. Zambon, F.T.; Meadows, T.D.; Eckman, M.A.; Rodriguez, K.M.R.; Ferrarezi, R.S. Automated ebb-and-flow subirrigation accelerates citrus liner production in treepots. *Agric. Water Manag.* **2022**, *262*, 107387. [CrossRef]
14. Zhang, G.; Dai, R.; Ma, W.; Fan, H.; Meng, W.; Han, J.; Liao, Y. Optimizing the ridge–furrow ratio and nitrogen application rate can increase the grain yield and water use efficiency of rain-fed spring maize in the Loess Plateau region of China. *Agric. Water Manag.* **2022**, *262*, 107430. [CrossRef]

15. Qiang, S.; Zhang, Y.; Zhao, H.; Fan, J.; Zhang, F.; Sun, M.; Gao, Z. Combined effects of urea type and placement depth on grain yield, water productivity and nitrogen use efficiency of rain-fed spring maize in northern China. *Agric. Water Manag.* **2022**, *262*, 107442. [CrossRef]
16. Sapino, F.; Pérez-Blanco, C.D.; Gutiérrez-Martín, C.; Frontuto, V. An ensemble experiment of mathematical programming models to assess socio-economic effects of agricultural water pricing reform in the Piedmont Region, Italy. *J. Environ. Manag.* **2020**, *267*, 110645. [CrossRef] [PubMed]
17. Zhong, H.; Sun, L.; Fischer, G.; Tian, Z.; Liang, Z. Optimizing regional cropping systems with a dynamic adaptation strategy for water sustainable agriculture in the Hebei Plain. *Agric. Syst.* **2019**, *173*, 94–106. [CrossRef]
18. Biswas, T.; Bandyopadhyay, P.; Nandi, R.; Mukherjee, S.; Kundu, A.; Reddy, P.; Mandal, B.; Kumar, P. Impact of mulching and nutrients on soil water balance and actual evapotranspiration of irrigated winter cabbage (*Brassica oleracea* var. *capitata* L.). *Agric. Water Manag.* **2022**, *263*, 107456. [CrossRef]
19. Nouri, H.; Stokvis, B.; Galindo, A.; Blatchford, M.; Hoekstra, A. Water scarcity alleviation through water footprint reduction in agriculture: The effect of soil mulching and drip irrigation. *Sci. Total. Environ.* **2019**, *653*, 241–252. [CrossRef]
20. Zheng, Y.; Tian, Y.; Du, E.; Han, F.; Wu, Y.; Zheng, C.; Li, X. Addressing the water conflict between agriculture and ecosystems under environmental flow regulation: An integrated modeling study. *Environ. Model. Softw.* **2020**, *134*, 104874. [CrossRef]
21. Zamani, O.; Grundmann, P.; Libra, J.A.; Nikouei, A. Limiting and timing water supply for agricultural production—The case of the Zayandeh-Rud River Basin, Iran. *Agric. Water Manag.* **2019**, *222*, 322–335. [CrossRef]
22. Abou-Shady, A.; El-Araby, H. Electro-agric, a novel environmental engineering perspective to overcome the global water crisis via marginal water reuse. *Nat. Hazards Res.* **2021**, *1*, 202–226. [CrossRef]
23. Abou-Shady, A. Recycling of polluted wastewater for agriculture purpose using electrodialysis: Perspective for large scale application. *Chem. Eng. J.* **2017**, *323*, 1–18. [CrossRef]
24. Abou-Shady, A. Reclaiming salt-affected soils using electro-remediation technology: PCPSS evaluation. *Electrochim. Acta* **2016**, *190*, 511–520. [CrossRef]
25. Nashwan, M.S.; Shahid, S. Future precipitation changes in Egypt under the 1.5 and 2.0 °C global warming goals using CMIP6 multimodel ensemble. *Atmos. Res.* **2022**, *265*, 105908. [CrossRef]
26. Fitton, N.; Alexander, P.; Arnell, N.; Bajzelj, B.; Calvin, K.; Doelman, J.; Gerber, J.; Havlik, P.; Hasegawa, T.; Herrero, M.; et al. The vulnerabilities of agricultural land and food production to future water scarcity. *Glob. Environ. Chang.* **2019**, *58*, 101944. [CrossRef]
27. Zarei, A.; Asadi, E.; Ebrahimi, A.; Jafari, M.; Malekian, A.; Nasrabadi, H.M.; Chemura, A.; Maskell, G. Prediction of future grassland vegetation cover fluctuation under climate change scenarios. *Ecol. Indic.* **2020**, *119*, 106858. [CrossRef]
28. Zhou, Z.; Ding, Y.; Shi, H.; Cai, H.; Fu, Q.; Liu, S.; Li, T. Analysis and prediction of vegetation dynamic changes in China: Past, present and future. *Ecol. Indic.* **2020**, *117*, 106642. [CrossRef]
29. de Santana, R.O.; Delgado, R.C.; Schiavetti, A. The past, present and future of vegetation in the Central Atlantic Forest Corridor, Brazil. *Remote Sens. Appl. Soc. Environ.* **2020**, *20*, 100357. [CrossRef]
30. Chen, C.-A.; Hsu, H.-H.; Liang, H.-C.; Chiu, P.-G.; Tu, C.-Y. Future change in extreme precipitation in East Asian spring and Mei-yu seasons in two high-resolution AGCMs. *Weather. Clim. Extrem.* **2022**, *35*, 100408. [CrossRef]
31. Clery, D. Greenhouse–Power Plant Hybrid Set to Make Jordan's Desert Bloom. *Science* **2011**, *331*, 136. [CrossRef] [PubMed]
32. SFP. The Sahara Forest Project. 2021. Available online: https://www.saharaforestproject.com/ (accessed on 1 September 2022).
33. Zhang, H.; Xu, Y.; Kanyerere, T. A review of the managed aquifer recharge: Historical development, current situation and perspectives. *Phys. Chem. Earth Parts A/B/C* **2020**, *118*, 102887. [CrossRef]
34. Vanderzalm, J.; Page, D.; Dillon, P.; Gonzalez, D.; Petheram, C. Assessing the costs of Managed Aquifer Recharge options to support agricultural development. *Agric. Water Manag.* **2022**, *263*, 107437. [CrossRef]
35. Hübner, U.; Wurzbacher, C.; Helbling, D.E.; Drewes, J.E. Engineering of managed aquifer recharge systems to optimize biotransformation of trace organic chemicals. *Curr. Opin. Environ. Sci. Health* **2022**, *27*, 100343. [CrossRef]
36. Parker, A.; Pigois, J.-P.; Filmer, M.; Featherstone, W.; Timms, N.; Penna, N. Land uplift linked to managed aquifer recharge in the Perth Basin, Australia. *Int. J. Appl. Earth Obs. Geoinf.* **2021**, *105*, 102637. [CrossRef]
37. Qureshi, A.S. Challenges and Prospects of Using Treated Wastewater to Manage Water Scarcity Crises in the Gulf Cooperation Council (GCC) Countries. *Water* **2020**, *12*, 1971. [CrossRef]
38. Bogatin, J.; Bondarenko, N.P.; Gak, E.Z.; Rokhinson, E.E.; Ananyev, I.P. Magnetic Treatment of Irrigation Water: Experimental Results and Application Conditions. *Environ. Sci. Technol.* **1999**, *33*, 1280–1285. [CrossRef]
39. Taimourya, H.; Oussible, M.; Baamal, L.; Bourarach, E.H.; Hassanain, N.; Masmoudi, L.; El Harif, A. Magnetically treated irrigation water improves the production and the fruit quality of strawberry plants (Fragaria × ananassa Duch.) in the northwest of Morocco. *J. Agric. Sci. Technol.* **2018**, *8*, 145–156. [CrossRef]
40. Wang, Y.; Wei, H.; Li, Z. Effect of magnetic field on the physical properties of water. *Results Phys.* **2018**, *8*, 262–267. [CrossRef]
41. Ashraf, M.W. Magnetic treatment of irrigation water and its effect on water salinity. In Proceedings of the 2nd International Conference on Food and Agricultural Sciences, Auckland, New Zealand, 12 November 2014; IACSIT Press: Singapore, 2014; Volume 77, pp. 1–5. [CrossRef]
42. El-Zawily, A.E.-S.; Meleha, M.; El-Sawy, M.; El-Attar, E.-H.; Bayoumi, Y.; Alshaal, T. Application of magnetic field improves growth, yield and fruit quality of tomato irrigated alternatively by fresh and agricultural drainage water. *Ecotoxicol. Environ. Saf.* **2019**, *181*, 248–254. [CrossRef]

43. Ercan, I.; Tombuloglu, H.; Alqahtani, N.; Alotaibi, B.; Bamhrez, M.; Alshumrani, R. Magnetic field effects on the magnetic properties, germination, chlorophyll fluorescence, and nutrient content of barley (*Hordeum vulgare* L.). *Plant Physiol. Biochem.* **2022**, *170*, 36–48. [CrossRef] [PubMed]
44. Shahin, M.M.; Mashhour, A.M.A.; Abd-Elhady, E.S.E. Effect of magnetized irrigation water and seeds on some water properties, growth parameter and yield productivity of cucumber plants. *Curr. Sci. Int.* **2016**, *5*, 152–164.
45. Luo, X.; Li, D.; Tao, Y.; Wang, P.; Yang, R.; Han, Y. Effect of static magnetic field treatment on the germination of brown rice: Changes in α-amylase activity and structural and functional properties in starch. *Food Chem.* **2022**, *383*, 132392. [CrossRef] [PubMed]
46. Liu, Y.; Pan, L.-M.; Liu, H.-B. Water electrolysis using plate electrodes in an electrode-paralleled non-uniform magnetic field. *Int. J. Hydrog. Energy* **2021**, *46*, 3329–3336. [CrossRef]
47. Kanany, R.; El-Naqma, K.; Othman, M. Effect of Magnetic Irrigation Water and Nitrogen Fertilizer Forms on Maize (*Zea maize* L.) Growth, Yield and Nitrogen Utilization Rate. *J. Soil. Sci. Agric. Eng.* **2017**, *8*, 383–389. [CrossRef]
48. Mostafa, H. Influence of magnetised irrigation water on the fertigation process and potato productivity. *Res. Agric. Eng.* **2020**, *66*, 43–51. [CrossRef]
49. Hamza, A.H.; Shreif, M.; El-Azeim, A.; Mohamad, M.; Mohamed, W.A. Impacts of Magnetic Field Treatment on Water Quality for Irrigation, Soil Properties and Maize Yield. *J. Mod. Res.* **2021**, *3*, 51–61. [CrossRef]
50. Maheshwari, B.L.; Grewal, H.S. Magnetic treatment of irrigation water: Its effects on vegetable crop yield and water productivity. *Agric. Water Manag.* **2009**, *96*, 1229–1236. [CrossRef]
51. Belessiotis, V.; Kalogirou, S.; Delyannis, E. Desalination Methods and Technologies—Water and Energy. *Therm. Sol. Desalin.* **2016**, *1*, 19.
52. Sharma, N.; Singh, A.; Batra, N. Modern and emerging methods of wastewater treatment. In *Ecological Wisdom Inspired Restoration Engineering*; Springer: Singapore, 2019; pp. 223–247. [CrossRef]
53. Abou-Shady, A.; El-Araby, H. *Treatment Technologies and Guidelines Set for Water Reuse*; IntechOpen: London, UK, 2023. [CrossRef]
54. Khor, C.S.; Akinbola, G.; Shah, N. A model-based optimization study on greywater reuse as an alternative urban water resource. *Sustain. Prod. Consum.* **2020**, *22*, 186–194. [CrossRef]
55. Khan, S.J.; Anderson, R. Potable reuse: Experiences in Australia. *Curr. Opin. Environ. Sci. Health* **2018**, *2*, 55–60. [CrossRef]
56. Rupiper, A.M.; Loge, F.J. Identifying and overcoming barriers to onsite non-potable water reuse in California from local stakeholder perspectives. *Resour. Conserv. Recycl. X* **2019**, *4*, 100018. [CrossRef]
57. Santana, M.V.E.; Cornejo, P.K.; Rodríguez-Roda, I.; Buttiglieri, G.; Corominas, L. Holistic life cycle assessment of water reuse in a tourist-based community. *J. Clean. Prod.* **2019**, *233*, 743–752. [CrossRef]
58. Ramprasad, C.; Rangabhashiyam, S. The role of sustainable decentralized technologies in wastewater treatment and reuse in subtropical Indian conditions. In *Water Conservation and Wastewater Treatment in BRICS Nations*; Elsevier: Amsterdam, The Netherlands, 2020; pp. 253–268. [CrossRef]
59. Hurtado, A.; Arroyave, C.; Peláez, C. Effect of using effluent from anaerobic digestion of vinasse as water reuse on ethanol production from sugarcane-molasses. *Environ. Technol. Innov.* **2021**, *23*, 101677. [CrossRef]
60. Li, Q.; Wang, W.; Jiang, X.; Lu, D.; Zhang, Y.; Li, J. Optimizing the reuse of reclaimed water in arid urban regions: A case study in Urumqi, Northwest China. *Sustain. Cities Soc.* **2019**, *51*, 101702. [CrossRef]
61. López-Morales, C.A.; Rodríguez-Tapia, L. On the economic analysis of wastewater treatment and reuse for designing strategies for water sustainability: Lessons from the Mexico Valley Basin. *Resour. Conserv. Recycl.* **2019**, *140*, 1–12. [CrossRef]
62. Maeseele, C.; Roux, P. An LCA framework to assess environmental efficiency of water reuse: Application to contrasted locations for wastewater reuse in agriculture. *J. Clean. Prod.* **2021**, *316*, 128151. [CrossRef]
63. Scales, P.J.; Wijekoon, K.; Ladwig, C.; Knight, A.; Allinson, M.; Allinson, G.; Zhang, J.; Gray, S.; Packer, M.; Northcott, K.; et al. A critical control point approach to the removal of chemicals of concern from water for reuse. *Water Res.* **2019**, *160*, 39–51. [CrossRef]
64. Aldaco-Manner, L.; Mohtar, R.; Portney, K. Analysis of four governance factors on efforts of water governing agencies to increase water reuse in the San Antonio Region. *Sci. Total Environ.* **2019**, *647*, 1498–1507. [CrossRef]
65. Dorzhiev, S.S.; Bazarova, E.G.; Pimenov, S.V.; Dorzhiev, S.S. Application of renewable energy sources for water extraction from atmospheric air. *Energy Rep.* **2021**, *7*, 343–357. [CrossRef]
66. Peeters, R.; Vanderschaeghe, H.; Rongé, J.; Martens, J.A. Fresh water production from atmospheric air: Technology and innovation outlook. *Iscience* **2021**, *24*, 103266. [CrossRef] [PubMed]
67. Bar, E. Extraction of water from air—An alternative solution for water supply. *Desalination* **2004**, *65*, 335. [CrossRef]
68. Esfe, M.H.; Esfandeh, S.; Toghraie, D. Numerical simulation of water production from humid air for Khuzestan province: Investigation of the Peltier effect (thermoelectric cooling system) on water production rate. *Case Stud. Therm. Eng.* **2021**, *28*, 101473. [CrossRef]
69. Zhang, L.; Song, X.; Zhang, X. Theoretical analysis of exergy destruction and exergy flow in direct contact process between humid air and water/liquid desiccant solution. *Energy* **2019**, *187*, 115976. [CrossRef]
70. Elashmawy, M. Experimental study on water extraction from atmospheric air using tubular solar still. *J. Clean. Prod.* **2020**, *249*, 119322. [CrossRef]
71. Zhao, H.; Lei, M.; Liu, T.; Huang, T.; Zhang, M. Synthesis of composite material HKUST-1/LiCl with high water uptake for water extraction from atmospheric air. *Inorganica Chim. Acta* **2020**, *511*, 119842. [CrossRef]

72. Scrivani, A.; Bardi, U. A study of the use of solar concentrating plants for the atmospheric water vapour extraction from ambient air in the Middle East and Northern Africa region. *Desalination* **2008**, *220*, 592–599. [CrossRef]
73. Sultan, A. Absorption/regeneration non-conventional system for water extraction from atmospheric air. *Renew. Energy* **2004**, *29*, 1515–1535. [CrossRef]
74. Poredoš, P.; Petelin, N.; Vidrih, B.; Žel, T.; Ma, Q.; Wang, R.; Kitanovski, A. Condensation of water vapor from humid air inside vertical channels formed by flat plates. *iScience* **2022**, *25*, 103565. [CrossRef]
75. Salehi, A.A.; Ghannadi-Maragheh, M.; Torab-Mostaedi, M.; Torkaman, R.; Asadollahzadeh, M. A review on the water-energy nexus for drinking water production from humid air. *Renew. Sustain. Energy Rev.* **2020**, *120*, 109627. [CrossRef]
76. Raveesh, G.; Goyal, R.; Tyagi, S. Advances in atmospheric water generation technologies. *Energy Convers. Manag.* **2021**, *239*, 114226. [CrossRef]
77. Chen, Z.; Song, S.; Ma, B.; Li, Y.; Shao, Y.; Shi, J.; Liu, M.; Jin, H.; Jing, D. Recent progress on sorption/desorption-based atmospheric water harvesting powered by solar energy. *Sol. Energy Mater. Sol. Cells* **2021**, *230*, 111233. [CrossRef]
78. Tu, Y.; Wang, R.; Zhang, Y.; Wang, J. Progress and Expectation of Atmospheric Water Harvesting. *Joule* **2018**, *2*, 1452–1475. [CrossRef]
79. Abou-Shady, A.; Peng, C.; Bi, J.; Xu, H. Recovery of Pb (II) and removal of $NO_3-$from aqueous solutions using integrated electrodialysis, electrolysis, and adsorption process. *Desalination* **2012**, *286*, 304–315. [CrossRef]
80. Abou-Shady, A.; Peng, C.; Xu, H. Effect of pH on separation of Pb (II) and $NO_3-$from aqueous solutions using electrodialysis. *Desalination* **2012**, *285*, 46–53. [CrossRef]
81. Abou-Shady, A.; Xu, H.; Peng, C. Production of pure water suitable for laboratory experiments by electrodialysis technology. In Proceedings of the 2011 5th International Conference on Bioinformatics and Biomedical Engineering, Wuhan, China, 10–12 May 2011; pp. 1–4. [CrossRef]
82. Zhiteneva, V.; Carvajal, G.; Shehata, O.; Hübner, U.; Drewes, J.E. Quantitative microbial risk assessment of a non-membrane based indirect potable water reuse system using Bayesian networks. *Sci. Total Environ.* **2021**, *780*, 146462. [CrossRef] [PubMed]
83. Ministry of Water Resources and Irrigation (MWRI). The Southern Valley Development (Toshka). 2020. Available online: https://www.mwri.gov.eg/toshka/ (accessed on 28 July 2023).
84. Wahby, W.S. Technologies Applied in the Toshka Project of Egypt. *J. Technol. Stud.* **2004**, *30*, 86–91. [CrossRef]
85. Labib, M.; Nashed, A. GIS and geotechnical mapping of expansive soil in Toshka region. *Ain Shams Eng. J.* **2013**, *4*, 423–433. [CrossRef]
86. Ellah, R.G.A.; Sparavigna, A.C. Combining bathymetric measurements, RS, and GIS technologies for monitoring the inland water basins: A case study of Toshka Lakes, Egypt. *Egypt. J. Aquat. Res.* **2022**, *49*, 1–8. [CrossRef]
87. Abo-Khalil, A.G.; Ahmed, S.S. Water-Pumping Using Powered Solar System—More Than an Environmentally Alternative: The Case of Toshka, Egypt. *J. Energy Nat. Resour.* **2016**, *5*, 19. [CrossRef]
88. Ellah, R.G.A. Morphometric analysis of Toshka Lakes in Egypt: A succinct review of geographic information systems & remote sensing based techniques. *Egypt. J. Aquat. Res.* **2021**, *47*, 215–221. [CrossRef]