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Enhancing Tomato Production by Using Non-Conventional Water Resources within Integrated Sprinkler Irrigation Systems in Arid Regions

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Citation: Abdelraouf, R.E.; Abdou, M.A.A.; Bakr, A.; Hamza, A.E.; Rashad, Y.M.; Abd-ElGawad, A.M.; Hafez, M.; Ragab, R. Enhancing Tomato Production by Using Non-Conventional Water Resources within Integrated Sprinkler Irrigation Systems in Arid Regions. *Atmosphere* **2024**, *15*, 722. https://doi.org/10.3390/atmos15060722

Academic Editors: Shengpei Dai and Zhizhong Zhao

Received: 28 April 2024
Revised: 27 May 2024
Accepted: 12 June 2024
Published: 16 June 2024

Abstract: This research evaluated the importance of establishing an integrated sprinkler irrigation design connected to fish farm ponds in order to achieve environmental and financial benefits. To achieve the aim of the study, two field experiments were conducted at a private farm in the Nubaria area of Beheira Governorate during the 2022 and 2023 seasons to quantify all the benefits from using fish water effluent (FWE) in irrigation. The obtained results indicated that the effluent could represent a good source of irrigation and bio-fertilization. The yield of tomato was higher when using FWE for irrigation compared with using groundwater for irrigation (IW). This was due to the additional amounts of dissolved bio-nitrogen along with other nutrients present in the FWE. The proportion of dissolved nitrogen added by using FWE was 22.3 kg nitrogen per hectare in 2022 and 24.6 kg nitrogen per hectare in 2023, in addition to some other major elements such as phosphorus and potassium, which are also among the main nutrients needed by crops. It has also been noticed that the fertility of the sandy soil increased with the use of FWE for irrigation. One of the most important results was the possibility of reducing the addition of nitrogen mineral fertilizers by 25%, thus saving on N fertilizers when growing tomato. In addition to the vitality of the FWE and its macro- and microelements, algae, microorganisms, and other organic materials, the use of this type of water as an alternative source for irrigation, along with the reduction in the amount of added mineral fertilizers, will reduce the degree of groundwater contamination with mineral fertilizers and increase the income of farmers. It was also observed that the air temperature decreased during the growing season when compared with the temperature of uncultivated surrounding areas.

Keywords: integrated designs; fish water effluent; sprinkler irrigation system; N fertigation technology; fish farms

1. Introduction

Arid and semi-arid areas are characterized by a high population density, in addition to a shortage of fresh water sources. Confronting these difficult factors constitutes a great challenge. There is an urgent need to reduce water consumption and use small quantities of fresh water sources for irrigation purposes [1–3]. The scarcity and limitations of fresh water pose a serious and major challenge to the production and cultivation of crops in semi-arid and arid regions [4,5]. Accordingly, it is very important to rationalize and reduce water consumption for all freshwater resources and wastewater in all its forms through the development of innovative and effective irrigation techniques [6]. One of the major challenges facing the agricultural sector is to increase crop production by irrigating with less fresh water, especially under the conditions of dry areas. There is a possibility to achieve this through increasing the productivity of crop yields per unit of water applied by irrigation [7]. The criterion of increasing and improving crop productivity per unit of irrigation water is important and vital, given the current conditions of scarce freshwater resources, in order to achieve and meet the growing demand for food, especially with the rapid increase in the population [8].

The arid climate requires advanced irrigation techniques in order to save water and increase crop yields [9,10]. One of the primary directions for saving water is to encourage the use of precision irrigation systems with the adoption of relevant technologies for semi-arid and dry regions [11].

In recent years, the use of unconventional water resources, such as wastewater, has increased in many countries of the world, especially in developing countries with arid climates. Numerous results have indicated that irrigation with liquid fish farm waste led to a significant and significant increase in the dry and wet weight of stems and roots and the number of leaves of cultivated plants compared with irrigation with conventional irrigation water. When using drainage water from fish farms, the plants' wet weight increased by 203% for basil and 250% for raffia, compared with those irrigated with river water [12]. The concentrations of nitrogen, potassium, phosphorus, manganese, and copper in basil and purslane plants increased significantly and significantly when using drainage water from fish farms compared with when irrigating with traditional irrigation water from rivers. Therefore, it is clear that the use of liquid waste from fish farms, when used as an alternative source of irrigation, will provide the water needs of plants, in addition to improving the soil's fertility by supplying it with the nutrients needed for crops [13].

Many countries have included the reuse of different wastewater in water resources plans. In the semi-arid and arid regions of the world, wastewater in all its forms is used in agriculture. The change of thought in looking at wastewater in a different way has led to paying more attention to the reuse of wastewater of fish farms' drainage water, as this type of water is rich in the organic matter and dissolved elements required for agricultural use, with the possibility of improving the soil's properties and fertility and the production of cultivated crops [14]. With a reduction in the costs required for the purchase of mineral fertilizers, it reduces the use of mineral fertilizers [15]. In order to meet the pressing needs and growing demand for protein sources, aquaculture has started in many arid and semi-arid countries. Throughout the ages, traditional farmers and investors have developed integrated farming systems that are managed and operated by advanced techniques and that, in most cases, have provided various sources of food security for the community while preserving agro-biological diversity and being environment-friendly [16].

The "integrated irrigated agriculture" concept, through which it is possible to improve the productivity and quality of the crop for each unit of water by raising fish in irrigation canals with the reuse of that water for different irrigation agricultural crops [17]. In addition, agricultural fish production can also take place in large tanks filled with water, which enables the reuse of the water for irrigation or when it is periodically changed and drained. As [18] explained, large ponds for fish farms are an integral part of the natural components of an active environment.

The shortage of freshwater resources, there is a need to devise sustainable strategies and new directions to search for non-traditional and new sources of irrigation [19]. There are many unconventional sources that can be used as an alternative to traditional irrigation water which have not sufficiently been exploited. One of the sources of this unconventional water is the wastewater of fish farms. The results have indicated the great benefits of this type of water, as it has been considered as an alternative irrigation method suitable for irrigating soybean crops, potatoes, onions, and various other crops. As a result of the dissolved vital nutrients and other fertilizer elements, in addition to the beneficial microorganisms that improve the quality and fertility of the soil, it has been used as an alternative source of fertilization as well, and thus the costs of purchasing mineral fertilizers were reduced. The experimental results indicated that a sprinkler irrigation system can be used when irrigating open fields with drainage water from fish farms for.

Plants grow on dissolved nutrients secreted directly by fish in their aquaria or generated by the decomposition of organic waste from fish. The fish filter nitrogen residues in the form of ammonia in the water inside the reservoirs through their gills. Active bacteria convert ammonia into nitrite and then into nitrate. Among the many benefits of aquaponic systems are the absorption of nutrients and dissolved elements by the plants grown, which reduces and reduces their discharge to the environment and prolongs the use and continuity of water without change (as the removal and extraction of various nutrients and dissolved nutrients through the absorption of plants can reduce the rate of exchange and change of water for breeding ponds of fish). With the integrated systems, the presence of a vegetable crop that receives the soluble nutrients required for its growth without additional costs improves the system's net profit. Continuous and daily use of fish feed leads to and provides a continuous supply of soluble nutrients to the cultured plants, thus eliminating the need to replace and change the nutrient solutions or modify and change the nutrient solutions as in hydroponic systems. These compounds result from complex and complex biological and biotic processes that involve and depend on the effective microbial degradation of organic matter, including vitamins, auxins, gibberellins, antibiotics, coenzymes, amino acids, organic acids, hormones, and other metabolites, which are directly absorbed and utilized by plants [20].

Through previous studies, important results have been found that express the extent to which drainage water from fish farms can be considered an important source and a good alternative to irrigation water. Wastewater discharged from fish farms' ponds is considered a vital source for fertilizing and irrigating with organic matter and dissolved nutrients. These vital components dissolved in the drainage water of fish farms can improve the soil's fertility, quality, and productivity. The organic content in the wastewater of fish-breeding farms also improves the cationic exchange capacity of sandy soils, thus facilitating the supply of nutrients to various cultivated plants. It is expected to increase the growth rate of plants grown and irrigated with the drainage water of fish farms better and faster when their roots absorb most of the nutrients and vital dissolved nutrients secreted by fish as well as organic and decomposing microbial waste [21].

This study aimed to evaluate the importance of establishing a newly developed integrated sprinkler irrigation system connected to fish farm ponds in order to achieve several environmental, health, and financial benefits. Our task was to determine what percentage of the drainage water from fish farms could be effectively captured and reused for irrigation and fertilization through an integrated sprinkler system.

2. Materials and Methods

2.1. Site Description

Climate: The field experiments were conducted from 2022 to 2023 on sandy soils at a private farm in the Nubaria area of Beheira Governorate, Egypt, located at 31°56′46.19″ N, 29°44′40.32″ E. The climatic parameters are given in Figure 1 (FAO, 2014).

Soil properties and water quality: The initial chemical and physical properties of the soil were determined at the beginning of the experiment, and the values are presented in Table 1. All average values for the chemical and biological properties of the irrigation water (IW) from a well were also measured, as shown in Table 2.

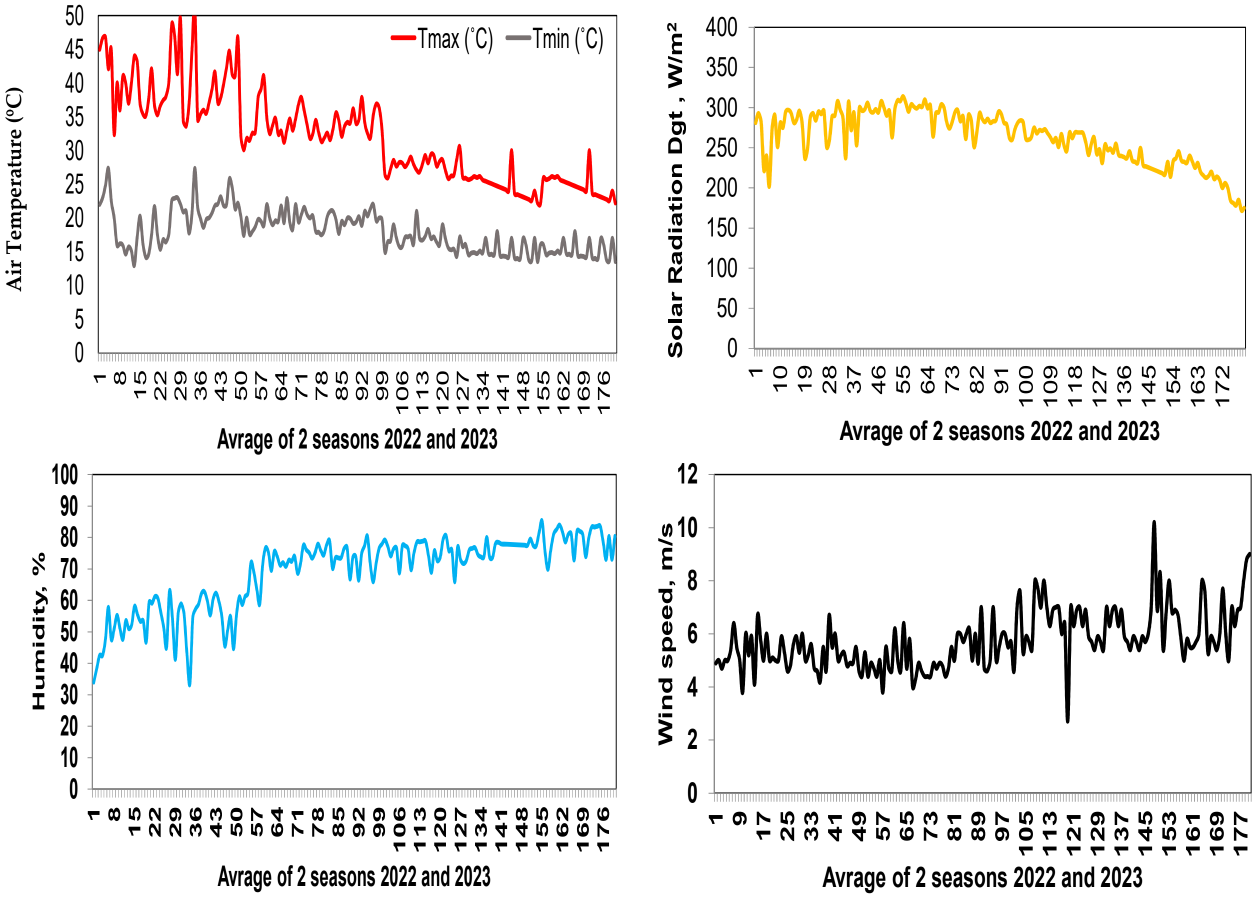

Figure 1. Climate data of the study site in the Nubaria area, Egypt.

Table 1. The soil's physical and chemical characteristics.

Items	Soil Depth, cm		
	0–20	20–40	40–60
Textural class		Sandy	
Coarse sand, %	47.86	54.72	38.75
Fine sand, %	49.65	41.68	57.48
Silt and clay, %	2.49	3.60	3.85
Bulk density, (BD), t m^{-3}	1.67	1.68	1.69
Electrical conductivity, (ECe), dS m^{-1}	0.67	0.69	0.72
pH, (1:2.5)	8.5	8.8	8.3
$CaCO_3$, %	7.3	4.69	4.62
Organic matter, OM, %	0.48	0.44	0.41

Type of fish and description of the dimensions of fishponds: The type of fish was tilapia (*Oreochromis niloticus*) and they were raised in 10 ponds, and the ponds' dimensions were 5 m wide × 15 m long × 2 m in depth but the volume of water inside the pond was 112.5 m^3 (5 m width × 15 m length × 1.5 m water depth), and the density of fish was 50 fish per cubic meter; the details are shown in Figure 2. The water resource of the fish farm is a groundwater well. The water effluent of these fishponds is disposed of when it is necessary to change the water and replace it with fresh water from the groundwater well by withdrawing it with an irrigation pump and conveying it to a sandy depression.

Table 2. Some chemical properties of the irrigation water from the underground well.

Chemical Properties	Value	Bio-Component Characteristics	CFU, mL^{-1}
EC, dS m^{-1}	0.61	Total bacteria	2460
pH	8.39	Total fecal coliforms	1980
Calcium, Ca^{2+} mg L^{-1}	1.06	Total fungi	97
Potassium, K^{+} mg L^{-1}	0.28	Total free N_2 fixers	59
Sodium, Na^{+} mg L^{-1}	2.45	Green algae	
Magnesium, Mg^{2+} mg L^{-1}	0.56	*Chlorella* sp.	89
Carbonate, CO_3^{2-} mg L^{-1}	<0.02	*Pediastrum* sp.	18
Bicarbonate, HCO_3^{-} mg L^{-1}	0.12	*Scenedesmus* sp.	16
Chloride, Cl^{-} mg L^{-1}	2.85	Cyanobacteria	
Sulfate, SO_4^{2-} mg L^{-1}	1.36	*Nostoc* sp.	<1
Nitrogen, g_N/m^3	<0.01	*Oscillatoria* sp.	15
Phosphorus, $P(PO_4^{3-})$ mg L^{-1}	0.29		

EC: electrical conductivity; CFU: colony-forming units.

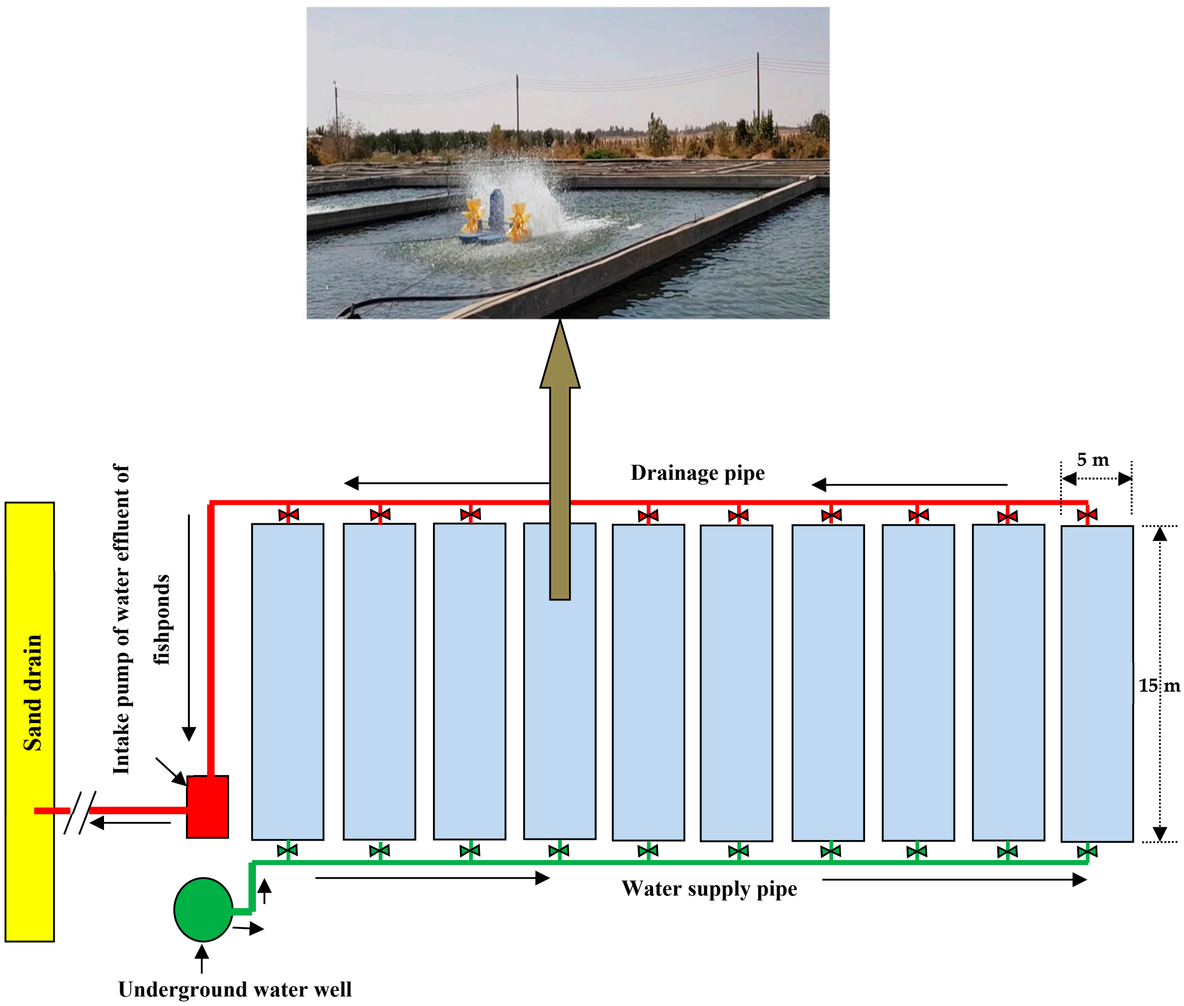

Figure 2. The layout of fish farm before development.

The fish farm under study contains 10 fishponds, and 20% of the total volume of water in these ponds was drained; therefore, the amount of water per day drained = 5 m × 15 m × 1.5 m × 0.2 × 10 ponds = 225 m^3 of FWE. The volume of the drained water per year = 225 m^3 × 365 day = 82,125 m^3/year.

Analysis of the fish farm effluent (FWE) revealed it could supply the soil with significant amounts of plant-available nutrients. The electrical conductivity (EC) of the FWE was measured at 1.94 dS/m, and the acidity (pH) was 7.14. Notably, the FWE contained 350.7 kg of total nitrogen (TN) per year, which represents the sum of all nitrogen forms, both organic (biological) and inorganic (chemical).

The biological nitrogen (bio-N) in the FWE refers to the nitrogen incorporated into organic matter, such as proteins, nucleic acids, and amino acids from living organisms or recently decomposed organic material. In contrast, the chemical nitrogen (chem-N) encompassed all inorganic forms of nitrogen, including nitrate (NO_3^-), nitrite (NO_2^-), ammonium (NH_4^+), and dissolved gaseous nitrogen, e.g., ammonia (NH_3).

This total nitrogen content of the FWE was equivalent to applying 1670 kg of ammonium sulfate fertilizer (21%N) annually. Additionally, the FWE provided 799.1 kg of phosphorus and 38.6 kg of potassium per year, demonstrating its potential as a valuable source of essential plant nutrients. It is worth noting that while nitrogen gas (N_2) is the most abundant form of nitrogen in the atmosphere, it is relatively unreactive due to the strong triple bond between the two nitrogen atoms. Specialized microorganisms play a crucial role in converting this atmospheric nitrogen gas into more reactive, plant-available forms through the process of nitrogen fixation.

Methane (CH_4), on the other hand, is not a form of nitrogen. It is a simple organic molecule composed of one carbon atom and four hydrogen atoms, and it can be a significant greenhouse gas if released into the atmosphere.

The use of this FWE as an alternative to freshwater irrigation has the potential to provide a sustainable and cost-effective way to supply the soil with the necessary nutrients for plant growth, while also reducing reliance on traditional fertilizers.

Biological properties of the fish water effluent: Quantitative measurements of the fungi and bacteria are shown in Table 3. The total number of bacteria was 16,500 CFU/mL in the fish farm wastewater, while it was 2300 CFU/mL in the irrigation water (IW). The total number of fecal coliform bacteria was 3300 CFU/mL in the fish farm wastewater, while it was 1900 CFU/mL in the irrigation water. The total number of fungi was 520 CFU/mL in the fishpond wastewater, while it was 90 CFU/mL in the irrigation water. The wastewater also contained algae, which, in turn, contained nutrients such as carbon, nitrogen, phosphorus, and potassium, which are important nutrients necessary for the growth and development of microorganisms.

Table 3. Bio-component properties of the fish water effluent and irrigation water.

Parameter	Fish Water Effluent (FEW)	Irrigation Water (IW)
	Bio-Characteristics, CFU, mL^{-1}	
Total no. of bacteria	16,500	2300
Total fecal coliforms	3300	1900
Total fungi	520	90

Components of the irrigation system: The irrigation network contained a submersible pump with discharge rate of 45 $m^3\ h^{-1}$. The main line (110 mm diameter) was to connect the irrigation water from the groundwater well to the sub-lines (75 mm in diameter). The irrigation water was transferred from the sub-line to the sprinkler line (63 mm in diameter). The design of the experiment included a sprinkler irrigation system with a nozzle diameter of 3/4″, a discharge rate of 1.15 m^3/h, a wetting radius of 10 m, and an operating pressure of 2.4 bar.

Fertilization method: Fertilizers for tomato plants were added, namely 150 kg of phosphorous per hectare in the form of superphosphate, and 250 kg of potassium was also added per hectare before planting; these were incorporated into the soil's surface layers. Moreover, nitrogen fertilizer at a rate of 320 kg nitrogen per hectare was applied in the form of ammonium nitrate and in a water-soluble form at an interval of 7 days through the sprinkler irrigation system using a Venturi injector. The application of N fertilizer started

2 weeks after planting in 12 equal doses, and the application stopped 40 days before the end of the growing season of tomatoes.

Experimental design: An experimental design was conducted for two seasons in 2022 and 2023 with the aim of maximizing the benefits of using fish water effluent (FWE) and evaluating the resource as an effective alternative to traditional irrigation with fresh water (IW). Three replicates of a split-plot design were used to set up the experiment. The main plots included two types of water allocated for irrigation; the first type was fish water effluent (FWE), and the second type was traditional fresh irrigation water (IW). The second factor for the study was the rate of mineral nitrogen fertilization, where four different rates of mineral nitrogen fertilizer (NMF) were added (100%N, 75%N, 50%N, and 25%N), as described as in Figure 3, which made up the main sub-plots.

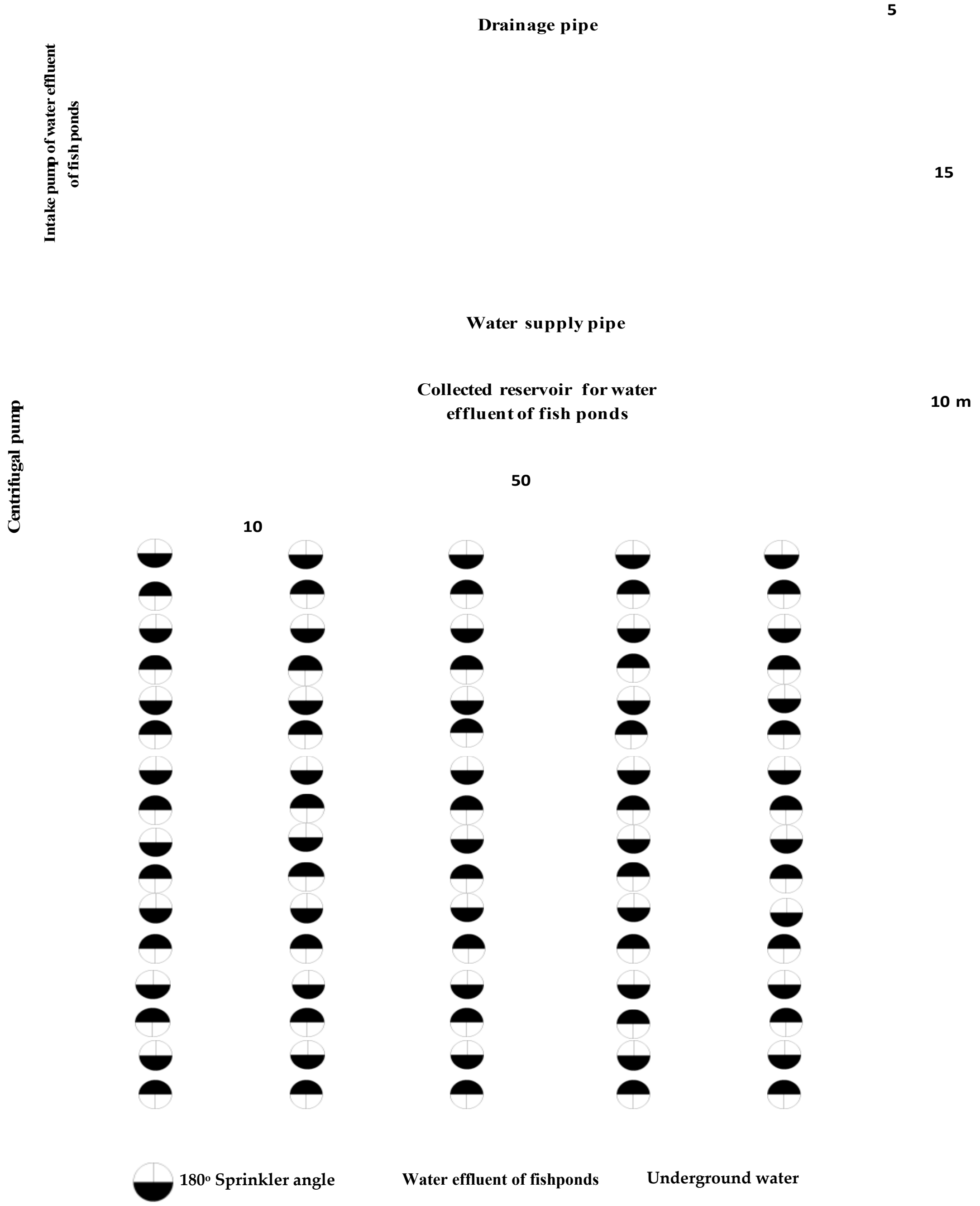

Figure 3. Layout of the experimental design to accurately determine the volume of mineral fertilizers to be added along with the nutrients and biological elements dissolved in the fish water effluent.

Gross irrigation requirements: The total volume of irrigation water for the sprinkler system for tomato production was obtained using Equation (1). The reference evaporation of the crop (ETo) obtained using the daily climate data was used as an input to the modified Penman–Monteith equation [19]. The tomato crop season has a duration of 155 days and it is divided into the following stages: primary, 30 days; evolutionary, 45 days; middle, 50 days; and the ripening of the fruits, 30 days. The crop coefficient was obtained during the two growing seasons, and they were 0.45, 0.75, 1.15, and 0.80 for the initial, developmental, middle, and late stages, respectively. The total volume of irrigation water during the two growing seasons was 5130 and 5100 m^3 ha^{-1}/season for season 2022 and 2023, respectively, for the sprinkler irrigation system. The frequency of irrigation was once per day.

$$IRg = [ET_O \times Kc]/I_E - R + LR \quad (1)$$

where IRg is the irrigation requirement in mm/day, ETo is the reference evapotranspiration in mm/day, Kc is the crop coefficient, I_E is the efficiency of sprinkler irrigation (90%), R is rainfall in mm/day, and LR is the volume of irrigation water required for the leaching process in mm/day.

2.2. Evaluation Parameters

Soil organic matter: The values of organic matter content were measured before planting, during the plants' growth stages, and after harvesting [20–22].

Activity of microorganisms in the root zone: To measure the total population of microorganisms in the root zone, soil samples were collected in three replicates from the rhizosphere of the grown crop in each of the treatment groups before harvest. The count of microorganisms (CFU) in each treatment was carried out at the end of the two tomato growing seasons Figure 4.

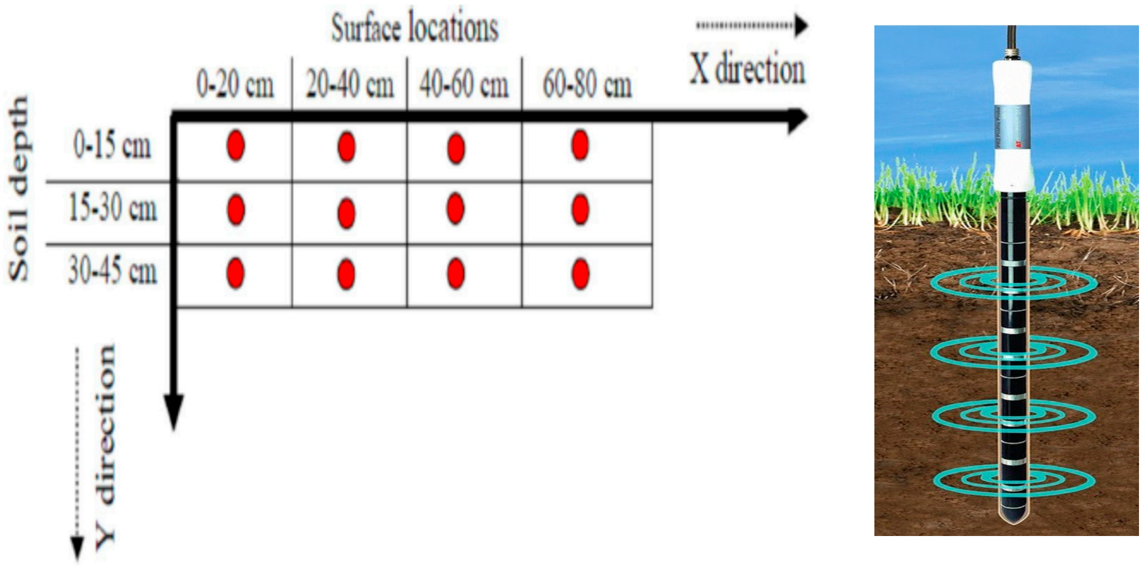

Figure 4. Measurements locations of soil moisture content using a profile probe.

Water application efficiency (WA_E): WA_E is defined as the ratio of actual water storage in the effective root zone to the water applied. WA_E was estimated using Equation (2)

$$WA_E = Ds/Da \quad (2)$$

where WA_E is the water application efficiency, Ds is the depth of stored water in the active root zone (mm), and Da is the depth of applied water in the active root zone (mm). Ds was calculated using Equation (3).

$$Ds = (\theta_1 - \theta_2) \times d \times \rho \quad (3)$$

where d is the depth of the soil layer (cm), θ1 is the average soil moisture content after irrigation (g/g) in the root zone, θ2 is the average soil moisture content before irrigation (g/g) in the root zone, and ρ is the relative density of the soil (g/cm^3).

Crop production: The productivity of the tomato crop was measured by estimating the productivity of an area of 1 m^2 from each experimental plot for each treatment, and the measurement unit for the productivity was kg/m^2. The productivity was converted to tons per hectare.

Water productivity of tomato: The water productivity of tomato was calculated according to [23] as follows

$$WP_{\text{tomato}} = Ey/Ir \quad (4)$$

where WP is the water productivity of tomato (kg tomato/m^3 water), Ey is the economic yield of tomato (kg ha^{-1}), and Ir is the applied volume of the irrigation water (m^3 water ha^{-1} per season).

To assess the impact of the experimental design on the microclimate within the cultivated area and its surroundings, a portable weather station was used. Air temperature was measured during the growing period, and Surfer software (version 8) was used to generate heat contour maps.

Statistical analysis: Most of the data's averages were subjected to statistical analysis in order to test the difference between the different treatments, as described by Snedecor and Cochran [24]. A joint statistical analysis test was also conducted for the results of the experiment for the years (2022 and 2023) using the method adopted by Steel and Torrie, where, through previous statistical tests, the average values were compared using the least significant differences (LSD) at a significance level of $p < 0.05$.

3. Results and Discussion

3.1. Soil Organic Matter

Figure 5 clearly indicates the positive impact of increasing the organic matter of sandy soil through irrigation with FWE compared with IW. This is a logical outcome resulting from the presence of organic matter, algae, and other substances with the FWE. There was a strong correlation between the decrease in organic matter in the soil and the decrease in the rate of mineral nitrogen supplementation. This may be due to the increase in the rate of absorption by the plants' roots from the decomposing organic nitrogen as the source of soil organic matter, and thus its concentration decreased in the root zone, which led to an increase in the rate of decomposition of organic matter in the soil, which resulted in a decrease in its content in sandy soil. The lowest values of soil organic matter content (SOMC) were observed when mineral nitrogen fertilization was supplied at a rate of 25% with IW, while the highest value of organic matter content in the soil was when mineral nitrogen fertilization was supplied at a rate of 100% with irrigation with FWE.

Moreover, the values of soil organic matter content for the second season (2023) were greater than the soil organic matter values for the first season (2022). This was due to the accumulation of organic matter in the sandy soil from the previous year [25].

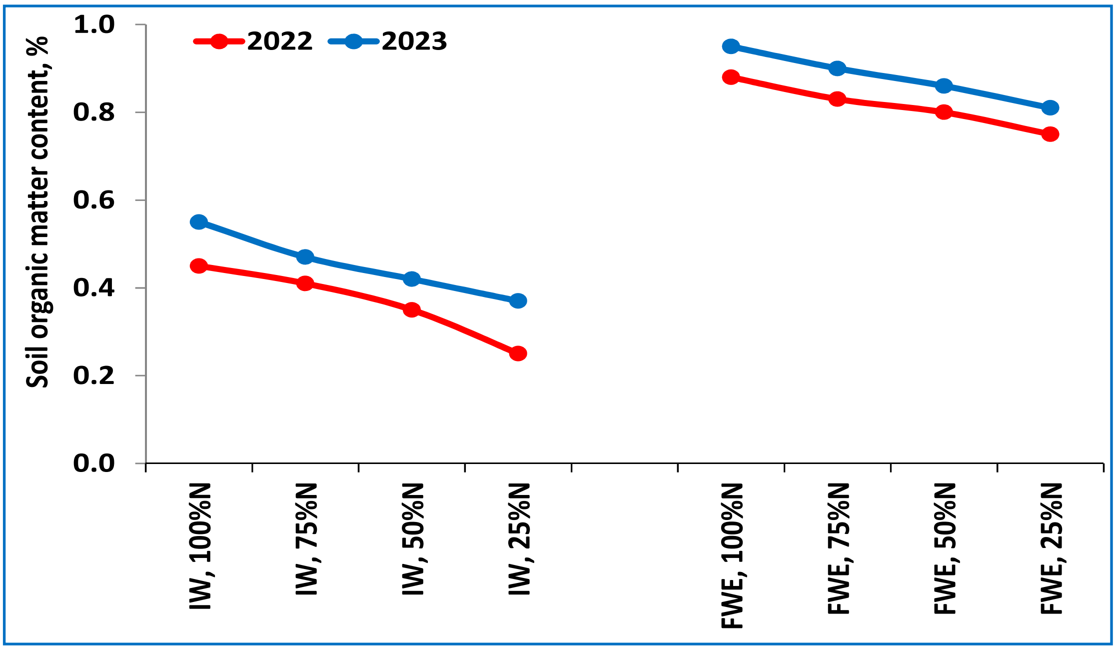

Figure 5. Impact of the application of fish water effluent (FWE) and nitrogen mineral fertilizers (NMF) on the soil organic matter content. Irrigation water, (IW).

3.2. Activity of Microorganisms in the Root Zone

In both growing seasons, the maximum and minimum numbers of microorganisms were observed. In the growth season of 2022, the maximum total number of microorganisms was 25 × 10^6 CFU per mL^{-1} under the FWE plus 100%N treatments, followed by the FWE plus 75%N treatment and the FWE plus 50%N treatment, with 22 × 10^6 and 17 × 10^6 CFU per mL^{-1}, respectively, while the minimum was 3 × 10^6 under the IW plus 25%N treatment (Figure 6). In 2023, the FWE plus 100%N treatment had the highest total number of microorganisms (40 × 10^6 CFU per mL^{-1}), followed by the FWE plus 75%N and FWE plus 50%N treatments, which had 29 × 10^6 and 24 × 10^6 CFU per mL^{-1}, respectively, and the minimum value of 7.3 × 10^6 was obtained under the IW plus 25%N treatment (Figure 7). In both growing seasons, the maximum and minimum numbers of colony-forming units (CFU) were observed for various bacterial colonies. The experimental media used for determination of the CFU differed from the media used for plant growth. Three replicates were performed for each treatment combination. In general, the number of microorganisms increased significantly for irrigation with fish farm wastewater compared with irrigation with fresh irrigation water, and this was certainly due to the increase in dissolved nutrients, algae, and organic materials in the fish farm wastewater. It was noted that the number of microorganisms decreased with a decrease in the application rate of mineral nitrogen fertilizers, and this may be due to the dependence of microorganisms on the nitrogen added to the soil as a source of energy and to complete their life cycle [26].

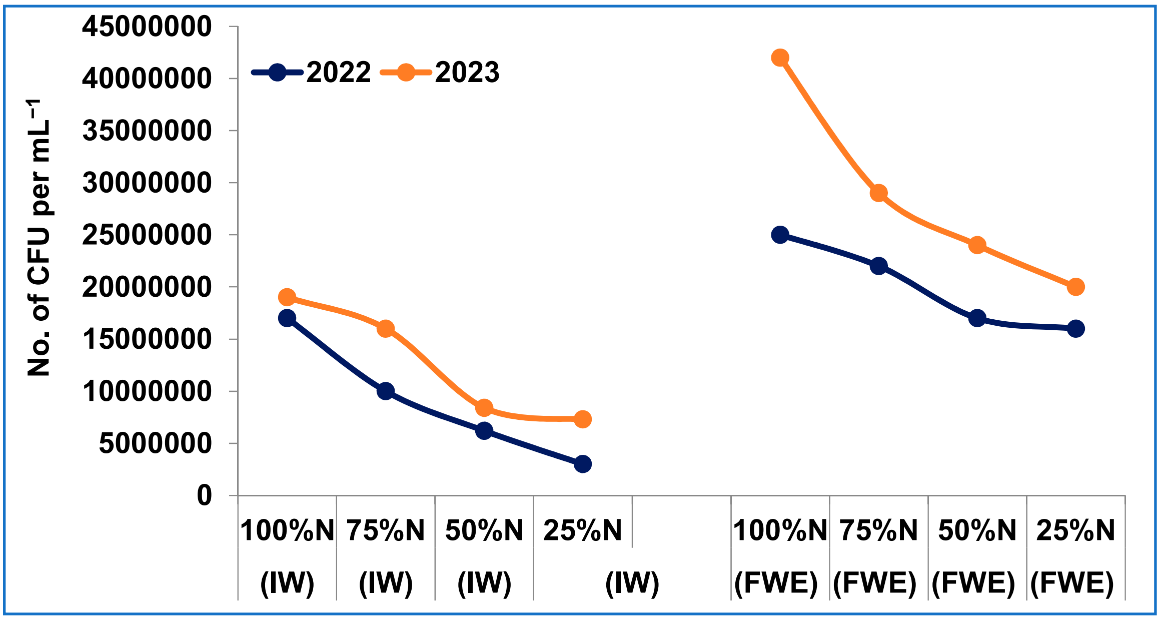

Figure 6. The number of colony-forming bacterial units (CFU) under the interaction of fish water effluent (FWE) and nitrogen mineral fertilizer (NMF) treatments.

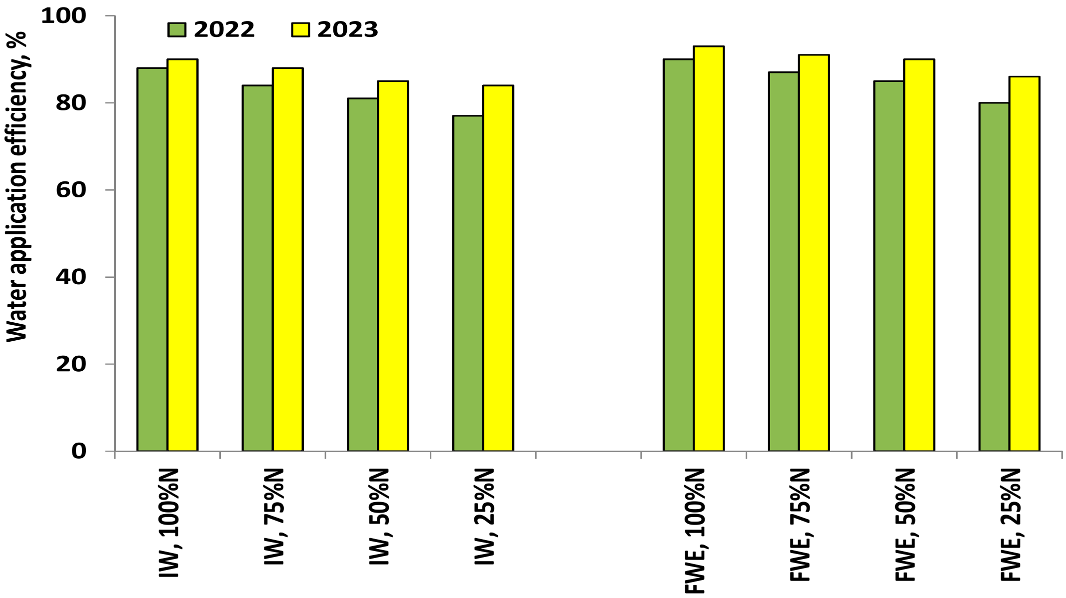

Figure 7. Impact of fish water effluent (FWE) and nitrogen mineral fertilizers (NMF) on the water application efficiency. Irrigation water, IW.

3.3. Water Application Efficiency

Figure 7 clearly shows the positive effect of the increase in the WAE under irrigation with FWE compared with IW. This was due to the increase in organic matter with the FWE. This may be attributed to two reasons. The first was an increase in organic matter with irrigation with FWE, which led to an increase in the water-holding capacity of the sandy soil, which led to an increase in the WAE values for irrigation with FWE compared with irrigation with IW. As for the second reason, it may be due to the increase in the size of the roots when the soil was irrigated with FWE as a result of the healthy environment rich in organic and vital materials, which led to an increase in the size of the roots' spreading area.

With a decrease in the application rate of nitrogen mineral fertilizers, the values WAE decreased. Perhaps this was due to the decrease in the size of the roots and the lower water uptake.

The lowest values of WAE were observed for mineral nitrogen fertilization at a rate of 25% and irrigation with IW, while the highest value of WAE was for mineral nitrogen fertilization at a rate of 100% and irrigation with FEW [27].

3.4. Crop Production

Figure 8 and Table 4 clearly show the positive effect of the increase in tomato production for irrigation with FWE compared with IW. This was due to the increase in the concentration of organic matter, algae, and dissolved nutrients in addition to the increase in WAE when using Few, which led to the creation of a fertile area rich in available nutrients and an increase in the soil's water-holding capacity. The latter resulted in an increase in the rate of absorption of nutrients needed by plants, which was reflected in an increase in productivity for irrigation with FEW compared with IW, which is poor in its content of nutrients and organic matter.

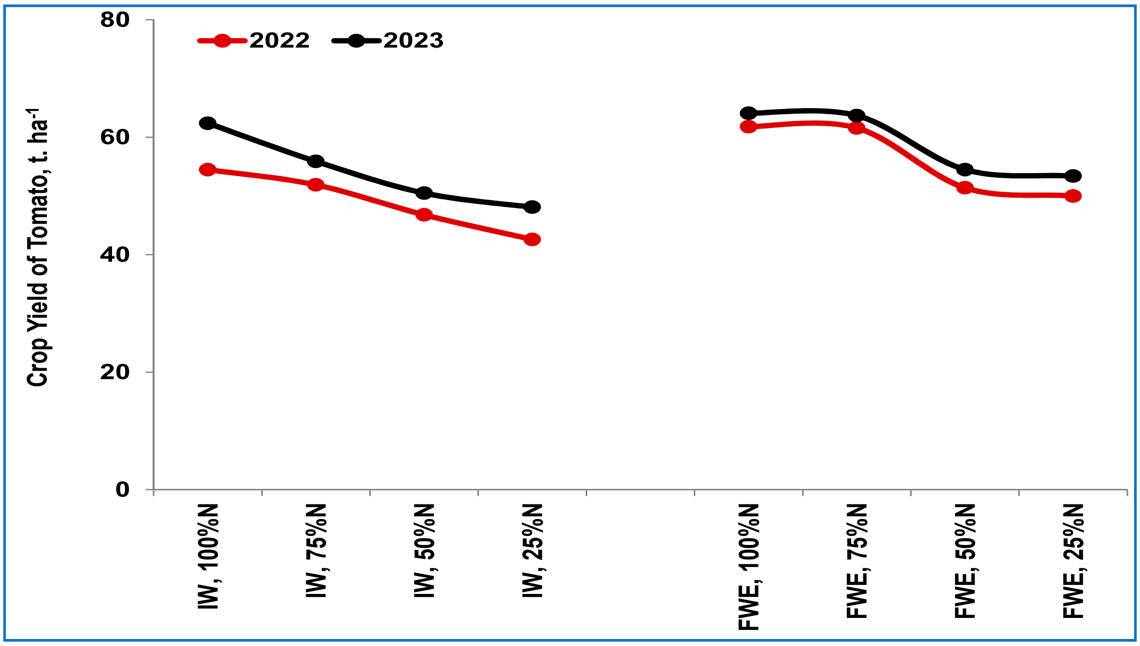

Figure 8. Impact of fish water effluent (FWE) and nitrogen mineral fertilizers (NMF) on the tomato yield. Irrigation water, IW.

Figure 9 and Table 4 also show that there is a strong relationship between tomato production and the decrease in the application rate of mineral nitrogen. This may have been due to the poor availability of nutrients needed to fertilize the cultivated plants.

The data presented in Table 4 show the extent of the effect of different rates of mineral nitrogen fertilization with irrigation water when using both FWE and IW to irrigate the tomato crop. No significant differences were found between the highest values for the yield of tomato under 100%N + FWE and 75%N + FEW during the two seasons (2022 and 2023) and the values of yield under 100%N + IW (control treatment). This was due to the increase in the amount of bio-dissolved nitrogen in the wastewater of the fish farms with the various bio-fertilizing elements. The amount of dissolved nitrogen in the FWE reached 22.3 kg nitrogen per hectare in the 2022 season, while it reached 24.6 kg nitrogen per hectare in the 2023 season, with the presence of additional phosphorus and potassium as major elements needed by most plants, especially tomato plants.

Table 4. Impact of fish water effluent and nitrogen mineral fertilizers on the yield and water productivity of tomato. All significant differences were statistically significant at $p < 0.05$.

Treatments		Yield, t ha^{-1}		Water Productivity kg $_{tomato}$ m^{-3} Water	
Water Quality	Nitrogen Mineral Fertilizer (NMF)	2022	2023	2022	2023
Impact of fish water effluent on the yield and water productively of tomato					
IW		48.95 b	54.22 b	9.54 b	10.63 b
FEW		56.20 a	58.92 a	10.95 a	11.57 a
LSD at α 0.05		0.434	1.490	0.096	0.314
Impact of nitrogen mineral fertilizer dosage on the yield and water productivity of tomato					
NMF1 (100%N)		58.15 a	63.25 a	11.33 a	12.42 a
NMF2 (75%N)		56.75 b	59.80 b	11.05 b	11.73 b
NMF3 (50%N)		49.10 c	52.50 c	9.58 c	10.30 c
NMF4 (25%N)		46.30 d	50.75 d	9.02 d	9.95 d
LSD at α 0.05		0.750	0.551	0.154	0.119

Note: Similar letters indicate that there are no significant differences, while different letters indicate that there are significant differences.

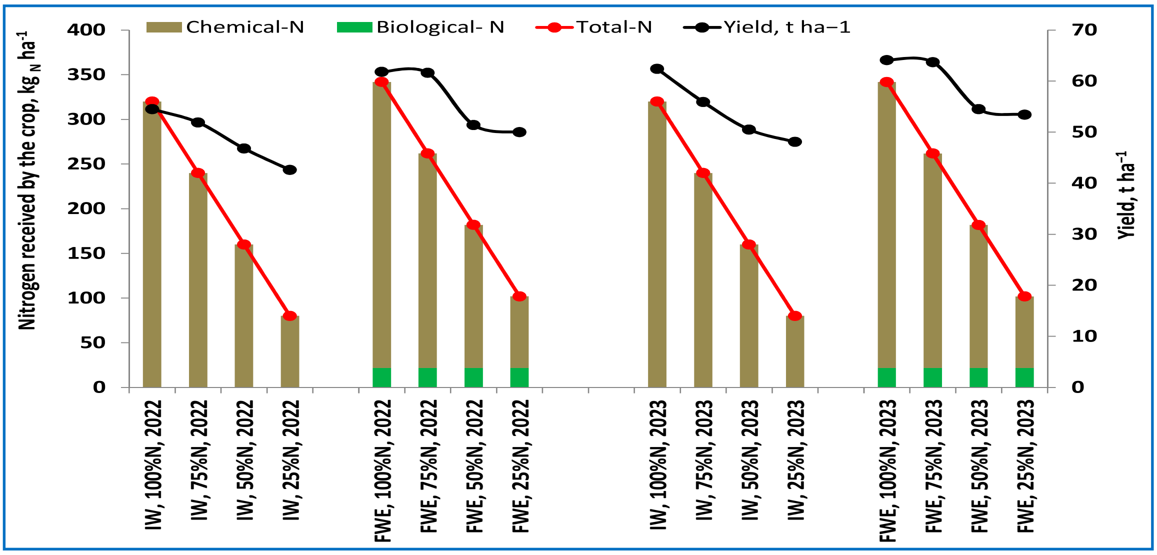

Figure 9. Impact of fish water effluent (FWE) and nitrogen mineral fertilizers (NMF) on the N fertilizer-based productivity of tomato. Fish water effluent, FWE; irrigation water, IW; nitrogen, N.

The obtained results were consistent with the results of other research and reports, which showed the importance of integrated agriculture (rice and fish farming) in building a healthy environment, as fish farming provided many organic materials that improved the properties of soil and increased its fertility [28]. In general, crop yields and total N uptake were increased by increasing the rate of nitrogen fertilization and saved at least 25% of mineral nitrogen fertilizers [29]. There is a possibility to increase the proportion of mineral fertilizers to more than 25% with summer crops, depending on what was observed in the initial evaluation stage of the quality of FWE, where it was found that the nutrients, algae, bacteria, and a number of microorganisms increased with the increase in the air temperature, which increased the activity of fish and their nutrition, the organic decomposition of feed residues, and the excretion and secretions of fish in the pond. The obtained results were consistent with other reports confirming that integrated paddy and fish farming is environmentally sound because the fish improve the soil's fertility by increasing the availability of nitrogen, phosphorous, and other necessary dissolved elements. In general, the crops' yield (tomatoes) as well as the total uptake of N were increased by increasing the fertilization rate.

3.5. Water Productivity of Tomato

Tables 4 and 5 indicates the tomatoes' water productivity values (WP_{tomato}), calculated as total amount of the yield in kg per m^3 of IW. The values of WP_{tomato} with the use of FWE as an alternative irrigation source were higher than the values obtained when using IW in both growing seasons, 2022 and 2023 [30].

Table 5. Impact of the interaction of fish water effluent and nitrogen mineral fertilizers on the yield and water productivity of tomato.

IW	NMF1 (100%N)	54.5 b	62.4 b	10.63 b	12.23 b
	NMF2 (75%N)	51.9 c	55.9 c	10.10 c	10.97 c
	NMF3 (50%N)	46.8 e	50.5 f	9.13 e	9.90 f
	NMF4 (25%N)	42.6 f	48.1 g	8.30 f	9.43 g
FEW	NMF1 (100%N)	61.8 a	64.1 a	12.03 a	12.60 a
	NMF2 (75%N)	61.6 a	63.7 a	12.00 a	12.50 a
	NMF3 (50%N)	51.4 c	54.5 d	10.03 c	10.70 d
	NMF4 (25%N)	50.0 d	53.4 e	9.73 d	10.47 e
LSD at α 0.05		1.060	0.780	0.218	0.169

FWE, fish water effluent; IW, irrigation water. Note: Similar letters indicate that there are no significant differences, while different letters indicate that there are significant differences.

3.6. Reusing Fish Water Effluent as a Bio-Source for Fertilization and Reducing Groundwater Pollution

Figure 9 and Table 6 show the positive impact of fish water effluent on increasing productivity and the quality of the crop fruits. The highest productivity values were obtained for irrigation with fish water effluent during the 2022 and 2023 growing seasons compared with irrigation with conventional irrigation water. The two highest values of yield were found for irrigation with fish water effluent with 100% and 75% of mineral nitrogen fertilization, and the difference between them was not significant. According to these results, it is recommended to irrigate with fish water effluent at a mineral nitrogen fertilization rate of 75%. This is, of course, due to the role of organic materials and dissolved elements in the wastewater from fish farming, which compensates for the shortage of 25% of the nitrogenous mineral fertilizers needed to fertilize tomato plants. As a result of the decrease in the amount of chemical mineral fertilizers added when the fish water effluent is used for irrigation, the amount of groundwater pollution with chemical fertilizers by deep percolation will be expected to decrease [31].

Table 6. Total water volume and amount of nitrogen applied for each treatment.

Irrigation Treatment	**Water Received by the Crop, m^3 ha^{-1}**	**Nitrogen Received by the Crop, kg N ha^{-1}**			**Yield, t ha^{-1}**
		Biological	**Chemical**	**Total**	
2022					
IW, 100%N	5130	0	320	320	54.5
IW, 75%N	5130	0	240	240	51.9
IW, 50%N	5130	0	160	160	46.8
IW, 25%N	5130	0	80	80	42.6
FWE 100%N	5130	21.9	320	341.9	61.8
FWE, 75%N	5130	21.9	240	261.9	61.6
FWE, 50%N	5130	21.9	160	181.9	51.4
FWE, 25%N	5130	21.9	80	101.9	50.0

Table 6. *Cont.*

Irrigation Treatment	Water Received by the Crop, m^3 ha^{-1}	Nitrogen Received by the Crop, kg N ha^{-1}			Yield, t ha^{-1}
		Biological	Chemical	Total	
2023					
IW, 100%N	5100	0	320	320	62.4
IW, 75%N	5100	0	240	240	55.9
IW, 50%N	5100	0	160	160	50.5
IW, 25%N	5100	0	80	80	48.1
FWE 100%N	5100	21.8	320	341.8	64.1
FWE, 75%N	5100	21.8	240	261.8	63.7
FWE, 50%N	5100	21.8	160	181.8	54.5
FWE, 25%N	5100	21.8	80	101.8	53.4

Fish water effluent, FWE; irrigation water, IW; nitrogen, N; N fertilizer productivity of tomato, N-FP tomato.

3.7. Improving the Microclimate of the Site after Implementing the Experimental Design

Figures 10 and 11 show the positive effect of the experimental design of the sprinkler irrigation system and its integration with the fish farm in reducing temperatures compared with normal temperatures outside the design area. It was also shown that there was a significant and positive effect of an increase in the amount of vegetative biomass due to the decrease in temperatures and the improvements in the microclimate's conditions.

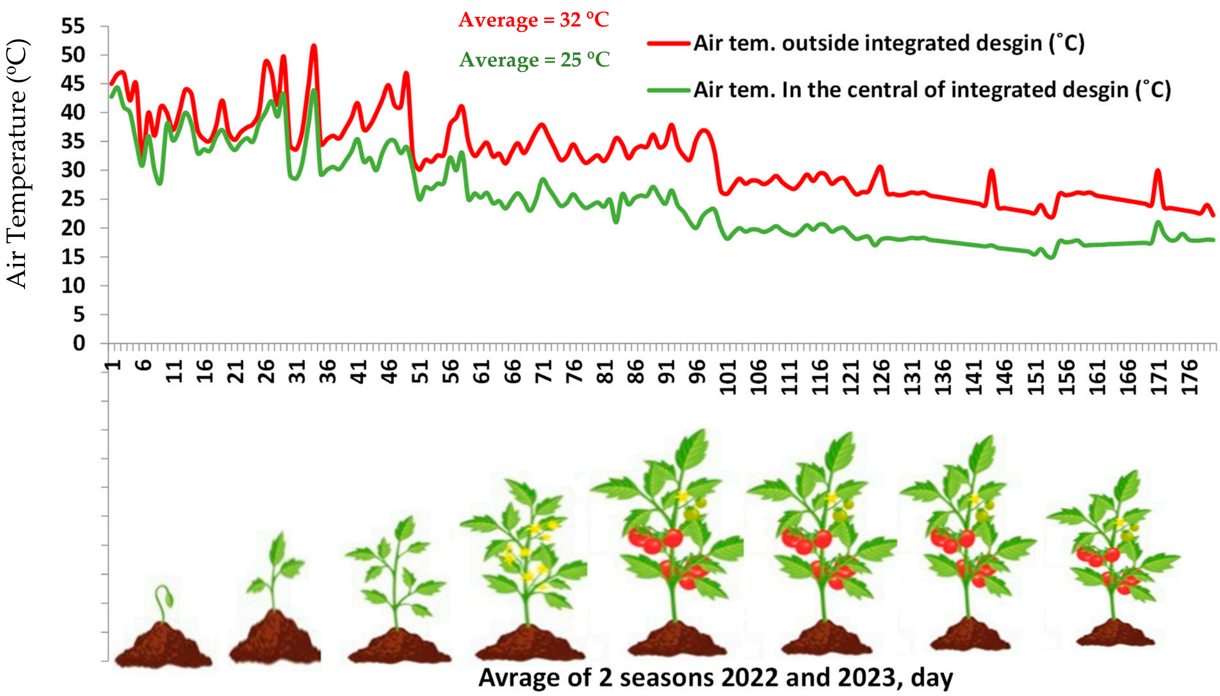

Figure 10. The impact of the integrated design of the sprinkler irrigation system on reducing air temperatures at the planting site and its relationship to the growth stages of cultivated plants.

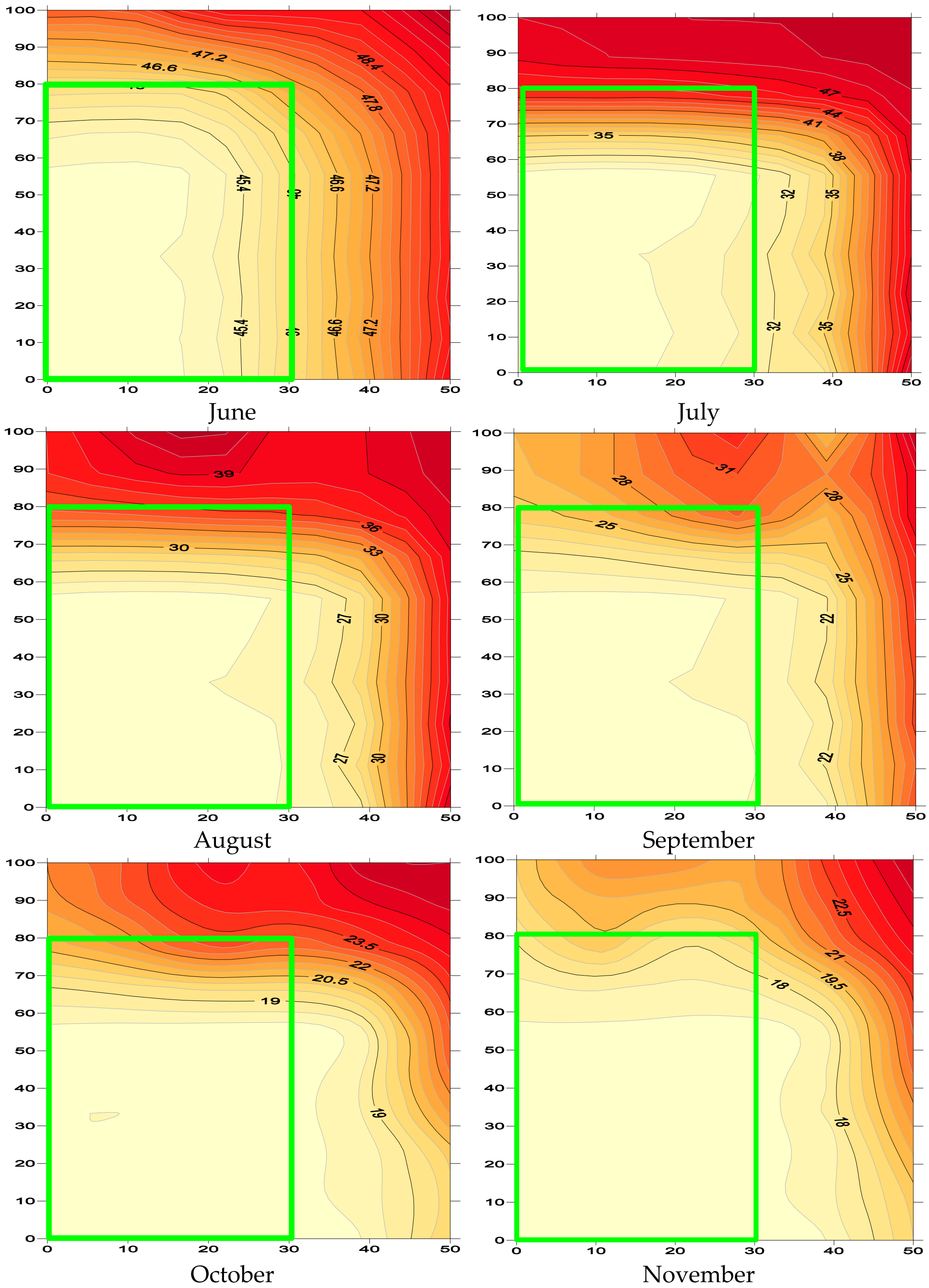

Figure 11. Contour maps of air temperature in the center and around the experimental design during the months of green growth (average of two seasons: 2022 and 2023). The green rectangle represents one-quarter of the experimental design.

These results indicated that the integrated sprinkler irrigation system was effective at moderating temperatures and creating a more favorable growing environment for the plants. The reduced temperatures and enhanced microclimate likely contributed to the observed increases in vegetative biomass. These findings suggest the integrated system design holds promise as an approach to maximize the utilization of drainage water from fish farms for irrigation and fertilization, while also improving growing conditions for the target plants.

In conclusion, this study has shown the viability of using an integrated sprinkler irrigation system to leverage drainage water from fish farms as an alternative water and nutrient source. The positive impacts on temperature regulation and plant growth demonstrated the potential benefits of this integrated system's design. Further research is warranted to optimize the system's parameters and evaluate its long-term performance [30,31].

4. Conclusions

It is clear from the results of studying the impact of the integrated sprinkler irrigation system on fish farms that it has many environmental and financial benefits. The environmental benefits were demonstrated in the improved properties and fertility of sandy soils with the organic matter, algae, and microorganisms dissolved in the fish water effluent, which contributed about 25% of the nitrogenous mineral fertilizer requirements, and the groundwater pollution rate was reduced by this amount of chemicals. We also noticed the relatively higher temperatures outside the bounds of the experimental area compared with the relatively lower temperatures inside the experimental area. Furthermore, the integration of sprinkler irrigation systems with fish farms makes it particularly suitable for adoption by small-scale farmers, contributing to overall economic sustainability in the Egyptian agricultural sector. The aim of this integrated design was to increase farms' income by increasing the productivity of integrated farms (plant production and fish production based on the reuse of fish water effluent in plant production) in addition to reducing the cost of purchasing mineral fertilizers by 25%.

Author Contributions: Conceptualization, A.E.H.; Software, M.A.A.A., A.B. and A.E.H.; Formal analysis, A.B.; Investigation, M.A.A.A. and R.E.A.; Data curation, A.E.H.; Writing—original draft, R.E.A. and R.R.; Writing—review & editing, Y.M.R., A.M.A.-E. and M.H.; Supervision, Y.M.R. and R.R. All authors have read and agreed to the published version of the manuscript.

Funding: This work was funded by King Saud University, Riyadh, Saudi Arabia, through The Researcher's Supporting Project (Number RSPD2024R676).

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Data that support the findings of this study are available from the corresponding author upon reasonable request.

Acknowledgments: The authors extend their appreciation to The Researchers Supporting Project number (RSPD2024R676), King Saud University, Riyadh, Saudi Arabia.

Conflicts of Interest: The authors declare no conflicts of interest.

References

1. Abdelraouf, R.E.; Okasha, E.M.; Tarabye, H.H.H. Modified Design for Drip Irrigation System to Improve the Productivity of Irrigation Water and Fertilizers Distribution. *Int. J. ChemTech Res.* **2016**, *9*, 40–52.
2. Abdel-Shafy, H.; El-Saharty, A.; Regelsberger, M.; Platzer, C. Rainwater in Egypt: Quantity, distribution and harvesting. *Mediterr. Mar. Sci.* **2010**, *11*, 245–257. [CrossRef]
3. Abdelraouf, R.E.; Abdou, S.M.M.; Mahmoud Abbas, M.M.; Hafez, M.M.; Popov, A.I.; Hamed, L.M.M. Influence of N-fertigation stress and agro- organic wastes (biochar) to improve yield and water productivity of sweet pepper under sandy soils conditions. *Plant Arch.* **2020**, *20* (Suppl. S1), 3208–3217.
4. Arafa, Y.; El-Gindy, A.G.M.; El-Shirbeny, M.; Bourouah, M.; Abd-ElGawad, A.M.; Rashad, Y.M.; Hafez, M.; Youssef, M.A. Improving the spatial deployment of the soil moisture sensors in smart irrigation systems using GIS. *Cogent Food Agric.* **2024**, *10*, 2361124. [CrossRef]
5. Youssef, M.A.; Peters, R.T.; El-Shirbeny, M.; Abd-ElGawad, A.M.; Rashad, Y.M.; Hafez, M.; Arafa, Y. Enhancing irrigation water management based on ETo prediction using machine learning to mitigate climate change. *Cogent Food Agric.* **2024**, *10*, 2348697. [CrossRef]
6. Alkhuzai, K.A.H. The Use of Organic Waste in Sustainable Water Management Under the Conditions of Dry Areas: Field and Modeling Study. *Arab. J. Sci. Eng.* **2022**, *48*, 5267–5287. [CrossRef]

7. Abdou, M.A.; Alashram, M.G.; Hamza, A.E.; Rashad, Y.M.; Abd-ElGawad, A.M.; Bourouah, M.; Hafez, M.; Abdelraouf, R.E. Using deficit irrigation strategies and adding sugarcane waste biochar as a sustainable material to sandy soils for improving yield and water productivity of cucumber. *Sustainability* **2024**, *16*, 4856. [CrossRef]
8. Abdelraouf, R.E.; Abou-Hussein, S.D.; Abd-Alla, A.M.; Abdallah, E.F. Effect of Short Irrigation Cycles on Soil Moisture Distribution in Root Zone, Fertilizers Use Efficiency and Productivity of Potato in New Reclaimed Lands. *J. Appl. Sci. Res.* **2012**, *8*, 3823–3833.
9. Omeir, M.K.; Jafari, A.; Shirmardi, M.; Roosta, H. Effects of Irrigation with Fish Farm Effluent on Nutrient Content of Basil and Purslane. *Proc. Natl. Acad. Sci. India Sect. B Biol. Sci.* **2019**, *90*, 825–831. [CrossRef]
10. Elnwishy, N.; Salh, M.; Zalat, S. Combating desertification through fish farming. The Future of Drylands. In Proceedings of the International Scientific Conference on Desertification and Drylands Research, Tunis, Tunisia, 19–21 June 2006.
11. Hafez, M.; Popov, A.I.; Rashad, M. Enhancing calcareous and saline soils fertility by. increasing organic matter decomposition and enzyme activities: An incubation study. *Commun. Soil Sci. Plant Anal.* **2022**, *53*, 2447–2459. [CrossRef]
12. Eid, A.R.; Negm, A. Improving Agricultural Crop Yield and Productivity of irrigation water via Sustainable and Engineering Techniques. In *Conventional Water Resources and Agriculture in Egypt*; The Handbook of Environmental Chemistry; Springer International Publishing AG: Cham, Switzerland, 2019; Volume 74, pp. 561–592. [CrossRef]
13. Altieri, M.A. Linking Ecologists and Traditional Farmers in the Search for Sustainable Agriculture. *Front. Ecol. Environ.* **2004**, *2*, 35–42. [CrossRef]
14. Xie, J.; Hu, L.; Tang, J.; Wu, X.; Li, N.; Yuan, Y.; Yang, H.; Zhang, J.; Luo, S.; Chen, X. Ecological mechanisms underlying the sustainability of the agricultural heritage rice–fish coculture system. *Proc. Natl. Acad. Sci. USA* **2011**, *108*, E1381–E1387. [CrossRef] [PubMed]
15. Bostock, J.; McAndrew, B.; Richards, R.; Jauncey, K.; Telfer, T.; Lorenzen, K.; Little, D.; Ross, L.; Handisyde, N.; Gatward, I.; et al. Aquaculture: Global status and trends. *Philos. Trans. R. Soc. B Biol. Sci.* **2010**, *365*, 2897–2912. [CrossRef] [PubMed]
16. Walia, S.; Kaur, N. Integrated Farming System—An Ecofriendly Approach for Sustainable Agricultural Environment—A Review. *Greener J. Agron. For. Hortic.* **2013**, *1*, 001–011. [CrossRef]
17. Vander Heijden, P.; Nasr Alla, A.; Kenawy, D. *Water Use at Integrated Aquaculture-Agriculture Farms: Experiences with Limited Water Resources in Egypt*; Global Aquaculture Alliance: Lynnwood, WA, USA, 2012.
18. Hafez, M.; Abdulla, A.A.; Abdulla, E.M.; Rashad, M. Influence of environmental-friendly bio-organic ameliorants on abiotic stress to sustainable agriculture in arid regions: A long term greenhouse study in northwestern Egypt. *J. King Saud Univ. -Sci.* **2022**, *34*, 102212. [CrossRef]
19. Lee, C.; Schaaf, T. The future of drylands. In Proceedings of the International Scientific Conference on Desertification and Drylands Research, Tunis, Tunisia, 19–21 June 2006; Springer Science & Business Media: New York, NY, USA, 2008.
20. Allen, R.G.; Pereira, L.S.; Raes, D.; Smith, M. Guidelines for computing crop water requirements. In *Irrigation and Drainage Paper*; John Wiley & Sons (Wiley): Hoboken, NJ, USA, 1998; Volume 56, 300p.
21. James, L.G. *Principles of Farm Irrigation System Design*; John Willey & Sons, Inc.: Hoboken, NJ, USA; Washington State University: Washington, DC, USA, 1988; pp. 73, 152–153, 350–351.
22. Atlas, R. *Handbook Media for Environmental Microbiology*; CRC Press, Taylor & Francis: Boca Raton, FL, USA, 2005.
23. American Public Health Association. *Standard Methods for the Examination of Water and Wastewater*, 20th ed.; American Public Health Association: Washington, DC, USA, 1998.
24. Snedecor, G.W.; Cochran, W.G. *Statistical Methods*, 7th ed.; Iowa State University Press: Ames, IA, USA, 1982; 511p.
25. Abdelraouf, R.E.; Azab, A.; Tarabye, H.H.H.; Refaie, K.M. Effect of pulse drip irrigation and organic mulching by rice straw on yield, water productivity and quality of orange under sandy soils conditions. *Plant Arch.* **2019**, *19*, 2613–2621.
26. Abdelraouf, R.E.; Abuarab, M.E. Effect of Irrigation Frequency under Hand Move Lateral and Solid Set Sprinkler Irrigation on Water Use Efficiency and Yield of Wheat. *J. Appl. Sci. Res.* **2012**, *8*, 5445–5458.
27. Hafez, M.; Rashad, M.; Popov, A.I. The biological correction of agro-photosynthesis of soil plant productivity. *J. Plant Nutr.* **2020**, *43*, 2929–2980. [CrossRef]
28. Giap, D.H.; Yi, Y.; Lin, C.K. Effects of different fertilization and feedingregimes on the production of integrated farming of rice and prawn Macrobrachium rosenbergii (De Man). *Aquac. Res.* **2005**, *36*, 292–299. [CrossRef]
29. Kizilkaya, R. Nitrogen fixation capacity of Azotobacter spp. strains isolated from soils in different ecosystems and re-lationship between them and the microbiological properties of soils. *J. Environ. Biol.* **2009**, *30*, 73–82.
30. Rashad, M.; Hafez, M.; Popov, A.I.; Gaber, H. Toward sustainable agriculture using extracts of natural materials for transferring organic wastes to environmental-friendly ameliorants in Egypt. *Int. J. Environ. Sci. Technol.* **2022**, *20*, 7417–7432. [CrossRef]
31. Ramadan, A.; Ghanem, H.G.; Bukhari, N.A.; El-Zaidy, M. Field and Modeling Study on Manual and Automatic Irrigation Scheduling under Deficit Irrigation of Greenhouse Cucumber. *Sustainability* **2020**, *12*, 9819. [CrossRef]