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Field and Modeling Study on Saving Mineral Fertilizers, Increasing Farm Income and Improving Soil Fertility Using Bio-Irrigation with Drainage Water from Fish Farms

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Abstract: The reuse of new and non-traditional sources of water for the purpose of irrigation is the primary goal of all countries that are located in dry areas and suffer from water scarcity, including Egypt in particular. This study was conducted to determine the appropriateness and quantify the benefits of using fish farm wastewater (DWFF), as an alternative to fresh irrigation water (IW), for the irrigation of barley. Two types of water quality were tested for the irrigation of barley, namely DWFF and IW, in addition to four levels of fertilization rates, 100%N, 80%N, 60%N, and 40%N, where 100%N represents 156 kg of nitrogen per hectare. The results showed a positive effect of increasing the nitrogen fertilization rate with irrigation water on the crop with the use of DWFF and IW for irrigating barley in two seasons: 2017/2018 and 2018/2019. The yield when using DWFF for the irrigation of barley was higher than the yield when using IW, which was in the range of 5.1% and 25.9% in 2017/2018 and between 9.8% and 33.3% in 2018/2019. This was due to the additional amount of dissolved biological nitrogen and other nutrients contained in DWFF. Notably, an additional amount of dissolved nitrogen is inherent in DWFF (12.81 kg nitrogen ha⁻¹ in 2017/2018 and 12.43 kg nitrogen ha⁻¹ in 2018/2019) and other elements, such as phosphorus and potassium, which are two macronutrients for crops. The SALTMed model was used to simulate soil moisture content, water application efficiency, nitrogen concentration in the soil layer in the effective root zone, N uptake, the dry matter of grown barley, and yield and water productivity for all treatments, with R² values of 0.94, 0.89, 0.99, 0.916, 0.89, 0.915, and 0.919 respectively. The research concluded that the use of DWFF is an effective alternative to IW for irrigating barley. It also helped to achieve higher yields while applying lower amounts of IW and chemical fertilizers. There are also additional benefits, such as reducing the drainage to the drainage network and increasing the income of farmers.

Keywords: drainage water; fertigation technology; fish farms; Nuptake; yield; barley; SALTMed model

1. Introduction

Arid regions are generally characterized by having high population densities and limited fresh water available. These factors put substantial pressure on the agricultural sector to reduce the consumption of limited amounts of fresh water for irrigation to allow water to be available to other

essential sectors [1–3]. Water scarcity is one of the serious challenges facing the cultivation and production of crops in dry areas. Therefore, it is important to rationalize and reduce the consumption of IW by developing innovative irrigation technologies that are effective at conserving water [4,5]. In Egypt, the agricultural sector faces the challenge of increasing food production using less water. This can be achieved by increasing the crop yield per unit of water. Increasing the productivity of crops per unit of water is vital under conditions of water scarcity to meet the increasing demand for food resulting from increases in the rate of population growth [6,7]. Egypt is suffering from severe water scarcity, and competition for scarce water resources is increasing as new irrigation techniques are being used to increase the productivity and quality of cultivated crops [8]. In the Arab Republic of Egypt, where average rainfall is very low, the productivity of crops per unit of water is very important [9]. The average annual rainfall is 12 mm, and it ranges from 0 mm per annum in the desert regions to 200 mm per annum in the north coastal regions. In addition, the maximum total volume of rain does not exceed 1.8 billion m³ per year [10]. The use of micro irrigation and related techniques should be promoted in arid regions, such as Egypt, to use a portion of IW to cultivate new areas [11–13].

Meanwhile, to meet the increasing demand for protein, aquaculture has been started in many semi-arid countries. Obviously, given the concerns for water resources in arid and semi-arid regions, increases in the number of aquaculture operations is exacerbating the problem of water availability for this purpose [14]. Over centuries, traditional farmers have developed diverse, locally adapted farming systems, which have been managed through ingenious practices that have often provided community food security and preserved agro-biodiversity [15]. It was found that the rice yield did not decline when fish production was below a threshold value in rice and fish intensive systems. Moreover, fish yields in intensive rice and fish systems can be much higher than those in traditional rice and fish systems without reducing the rice yield. In addition, the use of fertilizers, nitrogen (N), and pesticides has decreased, and the net income of farmers has increased [16,17]. However, new fish farms have contributed significantly to the food supply [18]. Nevertheless, to maintain the sustainability of IW, it may be necessary to focus on sustainable and integrated systems in which organic waste is used as an input for a different agricultural activity [19]. This can be achieved by establishing fish farming, in arid and semi-arid areas, that uses flushing irrigation ponds. In this context, the Food and Agriculture Organization FAO [20] reported on “Integrated Irrigated Agriculture” in which the productivity of the crop per unit of water can be improved by producing and raising fish in irrigation channels and re-using that water to irrigate agricultural crops. In addition, fish can be grown in slightly salty wastewater, which could possibly be used to irrigate crops. When fish farms are prohibited from keeping fish in irrigation canals, fish can be raised in water storage tanks. Then, water can be used for irrigation when it is time to change and drain those [21]. Fish ponds have additional functions: they attract wildlife and can be used for recreational activities and storing water that is used for irrigation. Fish can also be raised in tanks equipped for hydropower and irrigation. Some of the risks of this approach are that the fishes’ environment may be adversely affected as the water level inside the water tanks changes when it is used for irrigation [22]. However, this approach is being used in the Czech Republic and elsewhere, where large fish farm ponds are an integral part of the natural environment [23].

In addition to being a water source for irrigation, wastewater from fish farms is a good source of organic materials, and minerals from wastewater can improve soil quality, yield and crop quality, and reduce the cost of purchasing chemical fertilizers. Simultaneously, the content of organic matter (OM) in fish farm wastewater improves the ability of sandy soils to conduct cation exchange, thus providing cultivated plants with nutrients. Better growth of plants is expected when their roots absorb the dissolved nutrients excreted by fish and microbially decomposed organic waste [24].

The model of SALTMed by [25] is considered one of the most important models that have been developed, and it has proven its ability to simulate many crops under various field administrations, accounting for different irrigation systems, water characteristics, irrigation strategies, types of soils, crops, drainage systems, and fertilizer applications, and the effects of abiotic stresses, such as drought, salinity, extreme temperature, and shallow groundwater.

The current version of the model, which was released in 2015, allowed simultaneous simulations of 20 fields each with different irrigation systems, soils, crops, irrigation strategies, and N fertilizers. This model simulates soil moisture, dry matter, crop productivity, soil salinity, soil nitrogen dynamics, the requirements for salinity filtration, nitrate filtration, and drainage, soil temperature, evaporation, water absorption, water salinity, groundwater level, and effluent flow. This model was calibrated and validated using observed field data by [26–37]. They demonstrated the high predictability of field-measured yield, soil moisture, dry matter, and salinity.

This study aimed to determine the suitability and maximum benefit of using fish farm drainage water to reduce the need for mineral fertilizers and the total costs of production requirements in addition to improving soil fertility under dry conditions in Egypt through a field study and modeling using the SALT MED model.

2. Materials and Methods

2.1. Location and Climatic Data of the Experimental Site

Field experiments were conducted during the winter season of 2017/2018 and 2018/2019 at the research farm of the National Research Centre (NRC) (latitude $30^{\circ}30'1.4''$ N, longitude $30^{\circ}19'10.9''$ E, and 21 m above mean sea level at Nubaria Region, Al Buhayrah Governorate, Egypt. The experimental area has an arid climate with cool winters and hot dry summers. The maximum and minimum temperature, relative humidity, and wind speed were obtained from the local weather station at El-Nubaria Farm, as shown in Figure 1 and Table 1.

Figure 1. Area of the experimental site.

2.2. Chemical and Physical Properties of the Studied Soil and Water Quality of Two Types of Irrigation

The primary chemical and physical properties of the soil samples were identified and measured in situ and in the laboratory at the start of the field experiment (Table 2). The average values for the chemical, physical, and biological properties of fresh IW and fish farm wastewater were also measured, particularly during the effective period of barley fertilization, when a sample was taken every week until the number of samples reached seven samples during that period. The results for the analysis of the samples of fresh IW and DWFF showed that there were no significant differences between the fresh IW samples during the sampling period (effective fertilization period), while there were significant differences between the fish farm wastewater samples. These findings would be expected for different fish activity, feeding, and temperature, which change the content of this water from the dissolved elements, organic components, algae, and other vital components (Tables 3 and 4).

Table 1. Meteorological data for the research farm of the National Research Center (NRC) in Nubaria.

Meteorological Data	T _{MAX}		T _{MIN}		RAIN		WIND		RH	
Date	2017/2018	2018/2019	2017/2018	2018/2019	2017/2018	2018/2019	2017/2018	2018/2019	2017/2018	2018/2019
November	24.25	24.38	12.23	14.35	0	0	3.42	4.13	58.36	69.17
December	21.29	20.35	10.32	10.52	0	0	3.64	5.13	63.5	69.83
January	17.61	18.82	5.97	8.7	0	34.48	3.67	5.33	61.22	67.83
February	20.01	19.73	6.71	8.98	0	17.6	3.51	5.67	60.56	67
March	24.05	21.55	10.13	10.7	0	9.63	4.21	6.12	51.5	61
April	28.46	24.7	12.24	13.05	68.08	0	4.3	6.05	43.5	59
May	33.42	28.15	16.82	16.23	0	0	4.44	5.45	39.09	58.33
Total precipitation during the two growing seasons for barley to be deducted from the total amount of water calculated					68.08 mm = 681 m ³ ha ⁻¹		61.71 mm = 617 m ³ ha ⁻¹			

T_{MAX}: maximum air temperature (degrees C), T_{MIN}: minimum air temperature (degrees C), RAIN: average precipitation (mm/day), WIND: wind speed (m/s), RH: average relative humidity (%).

Table 2. Chemical and physical properties of the studied soil.

Parameter	Soil Depth (cm)			
	0–15	15–30	30–45	45–60
Physical properties				
Textural class	Sandy	Sandy	Sandy	Sandy
Coarse sand (%)	46.74	55.70	38.75	36.79
Fine sand (%)	50.78	40.68	57.44	59.10
Silt + clay (%)	2.48	3.62	3.81	4.11
BD (t m^{-3})	1.68	1.69	1.69	1.69
Chemical properties				
ECe (dS m^{-1})	0.37	0.33	0.45	0.47
pH (1:2.5)	8.6	8.7	9.1	9.2
CaCO_3 (%)	7.03	2.35	4.67	5.05
OMa (%)	0.64	0.42	0.27	0.25

BD: bulk density, OM: organic matter. All soil and water analyses were conducted in the laboratories of the National Research Center in Egypt.

Table 3. Some properties of drainage water from fish farms and fresh irrigation water.

Parameter	Drainage Water of Fish Farm (DWFF)	Irrigation Canal Water (IW)
E.C, dS m^{-1}	1.85	0.45
pH	8.21	7.38
Chemical properties, mg L^{-1}		
Calcium, Ca^{2+}	1.33	1.02
Potassium, K^{+}	0.51	0.22
Sodium, Na^{+}	2.52	2.44
Magnesium, Mg^{2+}	0.72	0.53
Carbonate, CO_3^{2-}	0.15	<0.01
Bicarbonate, HCO_3^{-}	0.40	0.10
Chloride, Cl^{-}	3.19	2.74
Sulfate, SO_4^{2-}	1.47	1.30
Nitrogen, $\text{g}_\text{N}/\text{m}^3$ $\text{NN}(\text{NH}_4^{+} + \text{NO}_3^{-})$	4.78	<0.01
Phosphorus, $\text{P}(\text{PO}_4^{3-})$	10.1	0.22
Copper, Cu^{++}	0.04	0.02
Ni $^{++}$	0.01	0.01
Zn $^{++}$	1.12	1.01
Magnesium, Mg^{2+}	0.72	0.53

E.C: electrical conductivity. All soil and water analyses were conducted in the laboratories of the National Research Center in Egypt.

2.3. Treatments and Experimental Design

The experimental design included eight treatments: two different types of IW and four fertigation rates with three replicates. The two types of water used were fresh irrigation water (IW) and drainage water from fish farms (DWFF). These water types were crossed with four nitrogen application rates: 100%, 80%, 60%, and 40%. For the 100% chemical N-fertilizer treatment, N was applied at the rate of 156 kg N ha^{-1} per season (Table 5) in ammonium nitrate form (33.5%N). We used 24 experimental plots, each with an area of 720 m^2 . The statistical design was a split design for this experiment. Soil moisture probe access tubes were placed in each pilot plot to measure the moisture content of the soil (Figure 2). Table 3 shows that DWFF was richer than IW in the major elements phosphorous, nitrogen, and potassium, which are essential nutrients for plants. It was also distinguished by micronutrients, such as nickel, zinc, and copper. In addition, it contained more microorganisms and

OM (Table 4). The sprinkler irrigation system with fish farm wastewater did not include a filtering unit to ensure that all the beneficial biological organic materials and algae were added to the sandy soil to improve the fertility of these poor sandy soils. The planting and harvesting dates for barley were the 20th of November and 14th of April for seasons 2017/2018 and 2018/2019, respectively. The growth period for barley was 146 days, with 20 days for the initial stage, 32 days for the development stage, 57 days for the middle stage, and 37 days for the late stage.

The type of fish used was tilapia (*Oreochromis niloticus*) and the specific variety is tilapia niloticus (Nile tilapia), raised in 12 ponds, and the dimension of the ponds were $5 \times 5 \times 2$ m, meaning that the volume of the ponds was 50 cubic meters, and the density of fish was 50 fish per cubic meter, meaning that the number of fish in one pond was 2500 fish, and the total number of fish in the experiment was 30,000 fish.

Table 4. Bio-component characteristics of the drainage water from fish farms and fresh irrigation water.

Parameter	Drainage Water Fish Farm (DWFF)	Irrigation Canal Water (IW)
Biological properties, counts as CFU (colony forming units), mL^{-1}		
Total bacteria	1.6×10^4	0.24×10^4
Total fecal coliforms	3.2×10^3	1.9×10^3
Total fungi	515	94
Total free N_2 fixers	606	55
Green algae	409	
<i>Chlorella</i> sp.		87
	122	
<i>Pediastrum</i> sp.		17
	153	
<i>Scenedesmus</i> sp.		12
Cyanobacteria	58	
<i>Nostoc</i> sp.		<1
	108	
<i>Oscillatoria</i> sp.		14

Table 5. Total amount of applied irrigation water and nitrogen for each treatment in the two studied seasons.

Treatment	Total Amount of Water Applied (m ³ ha ⁻¹)	Applied Nitrogen, kgN ha ⁻¹ , (2017/2018)			Total Amount of Water Applied (m ³ ha ⁻¹)	Applied Nitrogen, kgN ha ⁻¹ (2018/2019)		
		Biological	Chemical	Total		Biological	Chemical	Total
DWFF 100%N	2680	12.81	156	168.81	2600	12.43	156	168.43
DWFF, 80%N	2680	12.81	124.8	137.61	2600	12.43	124.8	137.23
DWFF, 60%N	2680	12.81	93.6	106.41	2600	12.43	93.6	106.03
DWFF, 40%N	2680	12.81	62.4	75.21	2600	12.43	62.4	74.83
IW, 100%N	2680	0	156	156	2600	0	156	156
IW, 80%N	2680	0	124.8	124.8	2600	0	124.8	124.8
IW,60%N	2680	0	93.6	93.6	2600	0	93.6	93.6
IW, 40%N	2680	0	62.4	62.4	2600	0	62.4	62.4

IW: fresh irrigation water; DWFF: drainage water of fish farms, N: Nitrogen.

Figure 2. Layout of experimental design.

2.4. Irrigation Requirements for Barley

The water applied using sprinkler irrigation, which was obtained from Equation (1), was 2680 m³/ha for the 2017/2018 season and 2600 m³/ha for the 2018/2019 season after deducting the amount of rainwater that fell during the two growing seasons for barley, *Hordeum vulgare*, variety Giza 123, where it was 681 m³ ha⁻¹ and was 617 m³ ha⁻¹ for the first and second season, respectively.

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

where IR_g is the gross irrigation requirements in mm/day, ET_O is the reference evapotranspiration in mm/day (estimated by the Central Laboratory for Climate, Agricultural Research Center, Egyptian Ministry of Agriculture at El-Nubaryia farm, following the Penman–Monteith equation), K_c is crop factor [38], I_E is irrigation efficiency in %, R is rainfall in mm, and LR is the amount of water required for the leaching of salts in mm.

2.5. Evaluation Parameters

2.5.1. Observed and Simulated Soil Moisture Content

The soil moisture content was determined using a profile probe at a depth of 0–30 cm and soil moisture was also simulated.

2.5.2. Observed and Simulated Water Application Efficiency

Water application efficiency (WA_E) is the proportion of water stored in the root zone of the water applied in the field. The WA_E was calculated using Equation (2):

$$WA_E = D_s / D_a \quad (2)$$

where WA_E is the water application efficiency (%), and D_s is the depth of stored water in the root zone (cm), calculated using Equation (3)

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

where D_a is the depth of applied water (mm), d is the soil layer depth (mm), θ_1 is the average of soil moisture content after irrigation (g/g) in the root zone, θ_2 is the average soil moisture content before irrigation (g/g) in the root zone and ρ is the bulk density of soil (g/cm³), while the simulated WA_E was calculated using Equation (2) for soil moisture content variables, D_s and D_a , before and after irrigation at different soil depths.

2.5.3. Observed and Simulated Dry Matter and Grain Yield of Barley

The dry matter and grain yield of barley was measured at harvesting time, and random samples for a sample area of 1 m² cm were examined from each plot to estimate dry matter and grain yields in kg/ha for the entire area of the experimental unit, which was then converted to yield per tonper ha. The simulated dry matter and grain yield of barley was measured using the different variables that are calculated and saved as output variables for dry matter and yield at harvesting time. Notably, dry matter was estimated every 15 days from the beginning of planting until harvest.

2.5.4. Observed and Simulated Water Productivity of Barley

The water productivity of barley was estimated following James (1988):

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

where WP_{barley} is the water productivity of barley (kg_{barley}/m³_{water}), Ey is the primary yield (kg/ha). Ir is the applied amount of the IW (m³_{water}ha⁻¹ per season). The water productivity of barley was also simulated using Equation (4) for different yields and levels of irrigation.

$$\text{Simulated } WP_{\text{barley}} = \text{Simulated } Ey/Ir \quad (5)$$

2.5.5. SALTMed Model

The SALTMed model [25] is freely downloadable from the Water4Crops EU funded project web site: <http://www.water4crops.org/saltmed-2015-integrated-management-tool-water-crop-soil-n-fertilizers/> and from the International Commission on Irrigation and Drainage, ICID, web site: http://www.icid.org/res_tools.html#saltmed_2015. During model calibration, the relevant SALTMed model parameters were fine-tuned against the observed data for soil moisture, dry matter, and crop yield. For calibration, IW + 100%N was selected. Various soil parameters, such as the hydraulic properties of sandy soils, were adjusted until a very close match was achieved between the actual and simulated soil moisture values. The parameters of the cultivated crop under study were also adjusted (Table 6). After a good fit for sandy soil moisture was achieved, only precise and specific control of the photosynthetic efficiency of barley dry matter and the actual yield of the crop were needed. The quality of the appropriate evaluation criteria used were the coefficient of determination (R^2), root mean square error (RMSE), and residual mass factor (CRM). The RMSE, R^2 and CRM values were recalculated using Equations (6)–(8) respectively.

$$RMSE = \sqrt{\frac{\sum (y_o - y_s)^2}{N}} \quad (6)$$

where y_o = predicted value, y_s = observed value, and N = total number of observations.

Table 6. The primary input parameters for barley for calibrating IW, 100%N (2017/2018), Egypt.

Barley	Growth Stage	Parameter
20 November 146	Initial	The sowing date of barley plant Number of days to harvest
20 32 57 37	Development Middle Late	Age stages of barley plants
0.32 1.15 0.27	Initial Middle End	Crop coefficient, Kc
0.68 3.5 3.12	Initial Middle End	Leaf area index, LAI
0 0.5 3.9		Mini. root depth, m Maxi. root depth, m Un-stressed crop yield, t h ⁻¹
0.85 0.45 0.7	Initial Middle End	Water uptake threshold
0.32 0.15 0.26 0.04 0.3 0 0.22 11 52		Harvest index Field capacity, m ³ m ⁻³ Saturated soil moisture content, m ³ m ⁻³ Wilting point, m ³ m ⁻³ Root width factor Residual water content, m ³ m ⁻³ Lambda pore size Bubbling pressure, cm Max. depth for evaporation, mm

The R² statistics demonstrate the ratio between the scatter of simulated values to the average value of measurements:

$$R^2 = \left\{ \frac{1}{N} \frac{\sum (y_o - \bar{y}_o)(y_s - \bar{y}_s)}{\sigma y_o - \sigma y_s} \right\} \quad (7)$$

where $\bar{y}_o$ = averaged observed value, $\bar{y}_s$ = averaged simulated value, σy_o = observed data standard deviation, and σy_s = simulated data standard deviation.

The coefficient of residual mass (CRM) is defined in Equation (8):

$$\text{CRM} = \frac{(\sum y_o - \sum y_s)}{\sum y_o} \quad (8)$$

Whenever these evaluation criteria are related to the following values, this indicates the high ability of this model to simulate the actual values. As for the full compatibility between the observed data and the simulation, the RMSE, CRM, and R² values should be equal to 0.0, 0.0, and 1.0, respectively.

2.6. Statistical Analysis

Most of the data were subjected to statistical analysis to clarify the discrepancy between the different treatments under study as described by Snedecor and Cochran [39]. A joint statistical analysis of the results for both seasons was conducted following the method adopted by Steel and Torrie [40], where the average values of the recorded data are compared using least significant differences (L.S.D with significance at <0.05).

3. Results and Discussion

3.1. Soil Moisture Content

Figure 3 shows the effect of water quality and nitrogen fertilization rate on the soil moisture content (SMC) of the barley root zone before irrigation under the maximum water requirements of the barley crop during the first growing season (2017/2018). The results for the second season (2018/2019) are not included in the figure, as they show similar outcomes.

Figure 3. Effect of water quality and fertilization rate of nitrogen on the soil moisture content before irrigation at peak during the 2017/2018 growing season compared with the simulated soil moisture content for all treatments: drainage water from fish farms (DWFF), fresh irrigation water (IW) and nitrogen (N).

When measuring the SMC under all the transactions under study, it was observed that they did not differ under the treatments that were irrigated with IW while the values were slightly higher under the transactions that irrigated using DWFF, and this may be due to the OM added with the DWFF keeping the water in the root zone in the sandy soil.

SMC did not change significantly with an increase in nitrogen fertilization rates. Perhaps this was due to the amount of water added being the same for all treatments for the same growing season.

Initially, the SMC was calibrated with IW + 100%N and validated against the other treatments for seasons 2017/2018 and 2018/2019. The model calibration simulated the SMC at a depth of 0–30 cm (Figure 4) for the studied soil for the 2017/2018 season, and the SMC was validated for the 2018/2019 season. The overall validation treatments for the SMC of the IW and DWFF treatments are shown here. The other treatments received the same amount of IW and showed very similar results (Figures 5 and 6). Overall, there was a close fit between the data simulated by the SALT MED model and the observed data during the calibration and validation processes. These results are similar to those obtained by [25,27,35–37,41,42].

Figure 4. Soil moisture calibration for fresh irrigation water and 100%N during the 2017/2018 season.

Figure 5. Observed and simulated soil moisture at a depth of 0–30 cm, during the 2017/2018 season, for overall validation treatments: drainage water from fish farms (DWFF), fresh irrigation water (IW) and Nitrogen (N).

Figure 6. Observed and simulated soil moisture at a depth of 0–30 cm depth, during the 2018/2019 season, for overall validation treatments: drainage water of fish farms (DWFF), fresh irrigation water (IW), and Nitrogen (N).

The SALTMED model demonstrated extremely high performance and sensitivity to simulate the SMC changes resulting from irrigation operations (Table 7), where the value of R^2 ranged from 0.89 to 0.94. The simulated and observed sandy soil moisture values for all treatments combined showed a significant and high correlation for the 2017/2018 and 2018/2019 growing seasons.

Table 7. Coefficient of determination (R^2), root mean square error (RMSE), and residual mass factor (CRM) coefficients for soil moisture in one layer depth (0–30 cm) for all irrigation treatments.

Date	Correlation Parameter	Drainage Water of Fish Farms				Irrigation Water			
		100%N	80%N	60%N	40%N	100%N	80%N	60%N	40%N
2017/2018	R^2	0.89		0.91			0.93		
	RMSE			−0.012			0.005		
	RCM			−0.017			−0.036		
2018/2019	R^2			0.92			0.94		
	RMSE			0.009			0.007		
	RCM			−0.015			−0.023		

3.2. Water Application Efficiency

For the two studied seasons, WA_E was investigated using different water qualities for irrigation and different rates of nitrogen fertilizer under sandy soil conditions.

WA_E increased under irrigation with DWFF in comparison to IW (Figure 7). This is likely due to the increase in the OM that was added as a result of irrigating with DWFF and the OM playing a vital role in increasing the water holding capacity and preventing nutrients leaching from the soil.

Figure 7. Effect of water quality and fertigation rate of nitrogen on the water application efficiency (WA_E) at the peak of irrigation during growing seasons and compared with simulated WA_E for all treatments for the 2017/2018 and 2018/2019 growing seasons for different treatments: drainage water from fish farms (DWFF), fresh irrigation water (IW), and nitrogen (N).

The effect of the fertigation rate of nitrogen on the WA_E is shown in Figure 7. WA_E decreased with a decreasing fertigation rate, which could be due to the increase in the fertigation rate increasing the size of the plants roots, enabling the absorption of most of the added IW and fertilizers.

There was a positive correlation between the simulated and observed values for both the 2017/2018 and 2018/2019 seasons (Figures 7 and 8), where the R^2 was 0.89, indicating the accuracy of the SALTMED model for simulating WA_E .

Figure 8. Observed versus simulated water application efficiency for all treatments for both seasons.

3.3. Nitrogen Concentration in the Soil Layer of the Effective Root Zone

Figure 9 shows that the N concentration of the soil layer (N-CSL) was affected for the 100%N, 80%N, 60%N and 40%N treatments for both the IW and DWFF treatments.

Figure 9. Observed and simulated nitrogen concentration of the soil layer for all treatments during the 2017/2018 and 2018/2019 seasons for different treatments: drainage water from fish farms (DWFF), fresh irrigation water (IW) and nitrogen (N).

The N-CSL values were higher in season 2017/2018 than season 2018/2019. This may be due to the increase in the amount of rain during the effective period of barley fertilization during the second growing season (2018/2019) when there was 34.48 mm of rain during January, which translates to 344.8 m³ ha⁻¹ and led to an increase in the rate of the leaching of fertilizer elements, including nitrogen, from the root zone. This led to a decrease in the N-CSL compared with the first season (2017/2018), in which the amount of rain that fell at the end of the growing season and outside of the effective

period of fertilization did not affect the concentration of fertilizer elements during the effective period of fertilization.

There was an improvement in the N-CSL with DWFF irrigation compared with IW irrigation in both the 2017/2018 and 2018/2019 seasons. This is due to the additional amount of biological nitrogen and other nutrients already present in the DWFF.

The N-CSL increased with increasing fertigation of N, which seems logical, as increasing the rate of N-Fertigation increases the N concentration in the root zone, leading to an increase in N.

After making a comparison between the actual N concentration values in the root diffusion region of the barley intakes measured using the field and simulated values given by the model (Figures 9 and 10), it was found that there was a high positive correlation between them during the 2017/2018 and 2018/2019 growing seasons, with an R^2 of 0.99.

Figure 10. Observed versus simulated nitrogen concentration of the soil layer for all treatments for two seasons.

3.4. Nitrogen Uptake

Nitrogen up take changed for the 100%N, 80%N, 60%N and 40%N treatments for both the IW and DWFF treatments (Figure 11).

Figure 11. Effect of water quality and nitrogen fertigation on N uptake during growing seasons and compared with simulated nitrogen uptake for the 2017/2018 and 2018/2019 seasons for all treatments: drainage water from fish farms(DWFF), fresh irrigation water (IW) and nitrogen (N).

The nitrogen uptake values were higher for the 2017/2018 season than the 2018/2019 season. This finding is likely due to the increase in the amount of rain water falling during the effective period of barley fertilization in the second growing season (2018/2019) when the amount of rainfall was 34.48 mm during January, which translates to $344.8 \text{ m}^3 \text{ ha}^{-1}$ and led to an increase in the rate of leaching of fertilizer elements, including N, from the root zone, which led to a decrease in the concentration of N. Previous influences led to a negative effect on the decrease of nitrogen uptake compared with the first season (2017/2018). For the 2018/2019 season, the amount of rain that fell at the end of the growing season and outside of the effective period of fertilization did not affect the concentration of fertilizer elements during the effective period of fertilization.

Total N uptake improved with the use of DWFF irrigation for barley compared with when irrigation with IW was used during growing seasons. This was due to the presence of excess and additional amounts of biological N in addition to other nutrients that were already present in the DWFF, with the additional N being estimated to be 12.81 kg of N per ha in the 2017/2018 season and 12.43 kg of N per ha in the 2018/2019 season compared with that for IW irrigation.

The total N uptake increased with an increasing fertigation rate of N, which seems logical, as increasing N-fertigation increases the concentration of N in the root zone, leading to increased nitrogen.

Figures 11–13 indicate that there was a positive correlation between the simulated and observed values of N uptake during the 2017/2018 and 2018/2019 seasons, with an R^2 of 0.916, which indicates that the SALTMED model quite accurately simulated the N uptake related to water quality and the fertigation rate of N.

Figure 12. Cont.

Figure 12. Observed and simulated accumulated-nitrogen uptake during 2017/2018 and 2018/2019 for all treatments: drainage water from fish farms (DWFF), fresh irrigation water (IW) and nitrogen (N).

Figure 13. Observed versus simulated accumulated-nitrogen uptake for all treatments for two seasons.

3.5. Barley Dry Matter

Table 8 shows that the average dry matter weight of barley was affected by the 100%N, 80%N, 60%N, and 40%N treatments for both the IW and DWFF treatments. The average weight of barley dry matter was higher when irrigating with DWFF than when irrigating with IW in the 2017/2018 and 2018/2019 seasons. This is due to the increase in N uptake under DWFF, because this water had additional bio-nitrogen and other bio-nutrients.

Table 8. Effect of water quality and nitrogen fertigation on the average weight of barley dry matter and compares it to simulated barley dry matter for all treatments.

Treatments		Observed Dry Matter-2017/2018, ton/ha		Simulated Dry Matter-2017/2018, ton/ha		Observed Dry Matter-2018/2019, ton/ha		Simulated Dry Matter-2018/2019, ton/ha	
Water quality	DWFF	11.9 a	±0.9			12.5 a	±1.0		
	IW	11.2 b	±1.1			11.5 b	±1.2		
LSD at α 0.05		0.3888				0.3513			
N-fertigation	100%N	12.5 a	±0.3			13.0 a	±0.4		
	80%N	12.4 a	±0.5			12.9 a	±0.6		
	60%N	11.2 b	±0.6			11.6 b	±0.7		
	40%N	10.3 c	±0.6			10.6 c	±0.7		
LSD at α 0.05		0.4412				0.5054			
Interaction	DWFF × 100%N	12.6	±0.4	13.1		13.2	±0.4	13.4	
	DWFF × 80%N	12.7	±0.2	13.0		13.4	±0.3	13.5	
	DWFF × 60%N	11.6	±0.6	12.2		12.2	±0.6	12.3	
	DWFF × 40%N	10.9	±0.1	10.1		11.2	±0.1	11.8	
	IW × 100%N	12.3	±0.2	12.3		12.7	±0.2	11.7	
	IW × 80%N	12.0	±0.3	12.1		12.4	±0.3	11.8	
	IW × 60%N	10.8	±0.3	11.0		11.1	±0.3	11	
	IW × 40%N	9.8	±0.3	9.9		10.0	±0.3	10.1	
LSD at α 0.05		N.S				N.S			
Equation, R ²		y = 1.152x – 1.642, R ² = 0.896				y = 0.883x + 1.331, R ² = 0.820			

N: Fertigation Rates of Nitrogen; IW: fresh irrigation water; DWFF: drainage water from fish farms.

The average weight of barley dry matter increased with increasing N uptake, which increased with increasing N-fertigation. The observed and simulated dry matter weights showed a good fit for all age stages of barley plants for most treatments. The SALTMed model simulated the dry matter values with an R^2 of 0.896 for all treatments for 2017/2018 and 0.82 for all treatments during 2018/2019 (Table 8).

3.6. Barley Yield

Figure 14 and Table 9 indicate the impact of N-fertigation rates with DWFF and IW irrigation on the yield of barley during the growing seasons of 2017/2018 and 2018/2019.

There was a strong positive effect on barley yield with increasing N-fertilization for DWFF and IW irrigation treatments in both growing seasons: 2017/2018 and 2018/2019. The barley yield under DWFF was higher than that under IW, increasing by 14.7%, with a range of 5.1%–25.9%, for the 2017/2018 season and increasing by 20%, with a range of 9.8%–33.3%, for the 2018/2019 season.

The biggest difference was related to the treatment with the least nitrogen. This was due to the excess and additional amount of dissolved bio-nitrogen in addition to the other bio-nutrients inherent in DWFF. Of note here is an additional amount of dissolved nitrogen inherent in DWFF (12.81 kg N ha⁻¹ in 2017/2018 and 12.43 kg N ha⁻¹ in 2018/2019) along with additional phosphorous and potassium. These findings are in agreement with the results of other reports showing that the integrated cultivation of rice and fish is environmentally sound and healthy, as fish farming improves soil quality and fertility by increasing the availability of nitrogen and [43,44]. In general, crop yields and total N uptake increased by increasing the rate of nitrogen fertilization.

Figure 14. Effect of water quality and the fertigation rate of nitrogen on the observed and simulated yield of barley for the 2017/2018 and 2018/2019 seasons for all treatments: drainage water of fish farms(DWFF); fresh irrigation water (IW) and Nitrogen (N).

The statistical analysis indicated that there were significant differences between crop yield values under all treatments during the two seasons:2017/2018 and 2018/2019. The yield was found to decrease for specific treatments for the 2017/2018 and 2018/2019 seasons:

DWFF + 100%N > DWFF + 80%N > IW + 100%N > IW + 80%N > DWFF + 60%N > DWFF + 40%N > IW+60%N > IW + 40%N. Figures 14 and 15 indicate that there is a strong correlation between the observed and simulated crop yield values for all treatments for the two growing seasons with a R^2 of 0.915 for all treatments.

Figure 15. Observed versus simulated yield for all treatments for seasons 2017/2018 and 2018/2019.

3.7. Water Productivity of Barley

Water productivity of barley (WP_{barley}) was estimated as the amount of grain yield in kg per m³ of applied IW. Figure 16 shows the impact of N-fertigation rates by using DWFF and IW on the WP_{barley} during 2017/2018 and 2018/2019.

Table 9. Effect of the water quality and nitrogen fertigation rate on the Harvest Index, grain yield, and water productivity of barley.

Treatments		H.I	Observed Yield, t ha ⁻¹		Simulated Yield, t ha ⁻¹	IRg = Irrigation – Rainfall, m ³ ha ⁻¹	Observed Water Productivity, kg _{grain} m ⁻³ water	Simulated Water Productivity, kg _{grain} m ⁻³ water	% Difference = [(DWFF – IW)/IW] × 100
2017/2018									
Water quality	DWFF		3.9 a	±0.4		2680	1.46		14.7
	IW		3.4 b	±0.5		2680	1.27		
LSD at α 0.05			0.1242						
N-fertigation	100%N		4.0 a	±0.2		2680	1.49		
	80%N		4.0 a	±0.2		2680	1.49		
	60%N		3.5 b	±0.2		2680	1.31		
	40%N		3.0 c	±0.5		2680	1.12		
LSD at α 0.05			0.2035						
Interaction	DWFF × 100%N	0.33	4.1	±0.2	4.3	2680	1.53	1.60	5.1
	DWFF × 80%N	0.33	4.2	±0.1	4.0	2680	1.57	1.49	10.5
	DWFF × 60%N	0.32	3.7	±0.1	3.6	2680	1.38	1.34	12.1
	DWFF × 40%N	0.31	3.4	±0.2	3.3	2680	1.27	1.23	25.9
	IW × 100%N	0.32	3.9	±0.1	3.8	2680	1.46	1.42	
	IW × 80%N	0.31	3.8	±0.1	3.9	2680	1.42	1.46	
	IW × 60%N	0.31	3.3	±0.1	3.5	2680	1.23	1.31	
	IW × 40%N	0.27	2.7	±0.4	2.8	2680	1.01	1.04	
LSD at α 0.05			N.S						
2018/2019									
Water quality	DWFF		4.2	±0.4		2600	1.62		20.0
	IW		3.5	±0.6		2600	1.35		
LSD at α 0.05			0.147						
N-fertigation	100%N		4.3	±0.2		2600	1.65		
	80%N		4.2	±0.3		2600	1.62		
	60%N		3.7	±0.3		2600	1.42		
	40%N		3.1	±0.6		2600	1.19		
LSD at α 0.05			0.2067						
Interaction	DWFF × 100%N	0.34	4.5	±0.1	4.7	2600	1.73	1.81	9.8
	DWFF × 80%N	0.34	4.5	±0.1	4.6	2600	1.73	1.77	15.4
	DWFF × 60%N	0.33	4.0	±0.1	3.7	2600	1.54	1.42	17.6
	DWFF × 40%N	0.32	3.6	±0.2	3.4	2600	1.38	1.31	33.3
	IW × 100%N	0.33	4.1	±0.1	4.4	2600	1.58	1.69	
	IW × 80%N	0.32	3.9	±0.2	4.0	2600	1.50	1.54	
	IW × 60%N	0.31	3.4	±0.1	3.3	2600	1.31	1.27	
	IW × 40%N	0.26	2.7	±0.4	2.5	2600	1.04	0.96	
LSD at α 0.05			N.S						

N: fertigation rates of nitrogen; IW: fresh irrigation water; DWFF: drainage water from fish farms.

Figure 16. Effect of water quality types and nitrogen fertilization rate on the observed and simulated water productivity of barley for the 2017/2018 and 2018/2019 seasons for all treatments: drainage water from fish farms (DWFF); fresh irrigation water (IW) and nitrogen (N).

There was a positive effect on the WP_{barley} , with an increased N-fertilization rate when using both DWFF and IW in both seasons: 2017/2018 and 2018/2019. The WP_{barley} under the DWFF treatments were higher than those under the IW treatments for the two growing seasons: 2017/2018 and 2018/2019.

The highest values of WP_{barley} were 1.57 and 1.73 kg m^{-3} for the DWFF + 80%N treatment for the 2017/2018 and 2018/2019 seasons, respectively. This is due to the highest productivity under the same conditions (DWFF + 80%N) and the stability of the amount of IW added to the same growing season.

There was a strong correlation between the observed and the simulation barley water productivity values, with an R^2 value of 0.919 for all treatments during the two barley growth seasons (Figure 17).

Figure 17. Observed versus simulated water productivity_{barley} for the 2017/2018 and 2018/2019 seasons for all treatments.

4. Conclusions

This pilot study investigated the suitability and optimization of irrigation using DWFF and IW for barley production through a field study using the SALTMED model.

The WAE increased under irrigation with DWFF compared to IW, which was likely due to the increase in the OM added with the DWFF to sandy soil, keeping the water in the root zone. WAE decreased by decreasing the fertilization rate of nitrogen, and this was likely due to an increase in the size of the roots of plants as a consequence of increasing the fertilization rate, enabling the absorption of most of the added IW and fertilizers. Total N uptake was improved with the use of DWFF compared

with IW for the irrigation of barley during the 2017/2018 and 2018/2019 growing seasons. This is likely due to the presence of additional biological N in addition to other nutrients that were already present in the DWFF. The total N uptake has been increased by increasing the N-fertilization rate and this seems logical, as increasing the rate of N-fertilization increases the concentration in the root zone and increases N uptake.

The obtained results indicate that there was a positive effect with increasing the rate of N-fertilization with irrigation water on crop yield using DWFF and IW in both seasons. However, the yield with irrigation using DWFF was higher than the yield under the IW treatment, for which the percentage increase in productivity ranked between 5.1% and 25.9% in 2017/2018 and between 9.8% and 33.3% in 2018/2019. The biggest difference was found for the treatment with the least nitrogen. Of note is an additional amount of dissolved nitrogen inherent in DWFF (12.81 kg N ha⁻¹ in 2017/2018 and 12.43 kg N ha⁻¹ in 2018/2019) along with more phosphorous and potassium. These findings are in agreement with the results of other reports that show that the integrated cultivation of rice and fish is environmentally sound and healthy, as fish farming improves soil quality and fertility by increasing the availability of N and phosphorous. In general, crop yields and total N uptake increased by increasing the rate of nitrogen fertilization. There was a positive impact on the WP_{barley} by increasing the fertilization rate under the DWFF and IW treatments in both seasons: 2017/2018 and 2018/2019. The WP_{barley} under DWFF was higher than the WP_{barley} under IW for two seasons: 2017/2018 and 2018/2019. The highest values of WP_{barley} were 1.57 and 1.73 kg m⁻³ for 2017/2018 and 2018/2019, respectively, which occurred under DWFF + 80%N. This may be due to the highest productivity under the same conditions (DWFF + 80%N) and the stability of the amount of IW added to the same growing season.

In summary, the SALTMED model simulated soil moisture, WA_E, N concentration within the barley plant root zone for sandy soil, N uptake, the weight of barley dry matter, and the productivity and water productivity of the barley crop and their R² values were 0.94, 0.89, 0.99, 0.916, 0.89, 0.915, and 0.919, respectively. The results obtained from the field study and the modeling data indicated that the yield from the use of DWFF has many benefits, which include improving yields and limiting the excessive use of mineral chemical fertilizers. These benefits have increased the income of ordinary farmers, in addition to reducing the volume of wastewater that must be disposed of in local sewage networks. Therefore, this study recommends the use fish culture wastewater for irrigation as a suitable alternative or supplement to limited freshwater resources and as a vital alternative to fertilization.

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