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Sustainable Solutions for Arid Regions: Harnessing Aquaponics Water to Enhance Soil Quality in Egypt

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Abstract: Dual use of water for fish and crop production could be a promising approach to improve irrigation under arid conditions. A watercress pot study was carried out to assess the effects of irrigation by catfish and tilapia aquaculture water on the sandy soil properties as well as the growth parameters of watercress with various combinations of artificial NPK fertilizers at El-Minia Governorate of Egypt (28°18′16″ N latitude and 30°34′38″ E longitude). Catfish aquaculture water had the greatest phytoplankton abundance at 83,762 units ($\times 10^4$/L), while the minimum number of phytoplankton existed in tilapia aquaculture water, recorded at 14,873 units ($\times 10^4$/L). There were significant average changes that varied from 120 to 237 ($\times 10^4$ cfu/mL^{-1}) in total bacterial counts in tilapia and catfish waters. Watercress growth quality parameters closely paralleled at all NPK application rates, indicating that the highest quality plants were produced in pots receiving 25% of the recommended levels and irrigated with catfish aquaculture water. Nitrate concentrations of watercress plants were determined under pollution levels established by the European Commission for leafy and tuber vegetables. In conclusion, the use of microbial and phytoplankton-rich aquaculture water to irrigate vegetables and as fertilizer can maintain a balanced soil ecosystem.

Keywords: sustainability; phytoplankton; watercress; soil quality; aquaponics

Citation: Abd El-Azeim, M.M.; Yousef, E.; Hussien, M.; Hamza, A.; Menesi, A.; Youssef, N.; Omar, M.; Lemanowicz, J.; Eldesoky, G.E.; Abdelkarim, N.S.; et al. Sustainable Solutions for Arid Regions: Harnessing Aquaponics Water to Enhance Soil Quality in Egypt. *Agriculture* **2023**, *13*, 1634. https://doi.org/10.3390/agriculture13081634

Academic Editors: Wen Yin, Zhandong Liu and Anzhen Qin

Received: 24 July 2023
Revised: 14 August 2023
Accepted: 17 August 2023
Published: 19 August 2023

1. Introduction

Egypt's expected population of 110 million people by 2023 will necessitate increased food production that will outpace the need for improved arable soil and water obtainability and quality [1]. Egypt is compelled to increase water productivity and utilize all poor-quality unconventional water supplies due to the pressures of a growing population and a food deficit [2]. The use of saline or brackish water for irrigation and aquaculture in areas with a limited supply of water requires the adoption of cutting-edge technology and environmentally friendly farming practices. Diverse approaches, such as aquaponics, are urgently required to increase water productivity [3,4]. Agriculture uses around 85% of the water allocation for the Nile, with irrigated agriculture being the main consumer. The situation is made worse by the fact that surface irrigation, the main irrigation technique used in the Nile Valley and Delta regions, even in desert sandy soils with application effectiveness below 50%, is severely depleting groundwater, a priceless resource [5].

Due to its fixed share of the Nile's water (55.5 billion m^3/year) and a lack of water resources, Egypt is currently experiencing serious problems and dealing with severe issues [2,6]. The Nile River has been the artery of life for the Egyptian population and any kind of sustainable development chiefly relies on the availability of Nile water. Water shortage occurs when there are not enough available water resources to meet the country's needs. There are two probable causes of a water deficit: an economic shortage of water, which results from inefficient management of the scarce water resources, or physical water scarcity, which is brought on by insufficient natural water supplies [5,7]. Egypt's water deficit is mostly physical since there are not enough water resources, and it is also economic because those resources are not managed well.

Despite the challenges associated with arid conditions, including an absence of water, poor soil fertility, the spread of sandy soils, deforestation, saline water, and low yields of crops, agricultural output remains one of the key elements influencing the economy and the availability of food. Large-scale agricultural areas in Egypt are subject to dry and semi-arid climate conditions, as well as severe salinization problems brought on by irrigation with subpar quality of water, inadequate drainage systems, and a lack of soil fertility or nutrient availability. Because of this, farmers in arid areas are being forced to find innovative ways to preserve water, increase crop quality, and do so without harming the environment [8,9].

In order to effectively manage irrigated agriculture in arid regions, attention must be diverted from maximizing output per unit of water spent to maximizing output per water drop consumed [5,6]. This will expand crop output globally and enhance agricultural irrigation techniques. In areas with limited rainfall, it is not just the quantity of water that is becoming scarce: it is also the quality of the water [6]. Using salty or brackish water continuously to grow crops increases soil salinity [10,11]. Agricultural soil productivity and crop value can be dramatically reduced by a soluble salt build-up in the soil and root rhizosphere. The persistent use of high-salinity, low-quality irrigation water is one of the major issues facing agriculture in many nations around the world [4,12].

Aquaculture uses water and is logically and coherently integrated with agriculture to become a non-consumptive producing sector that does not compete with agriculture, which increases the advantages of sustainable farming [13]. Due to the multiple uses of water in aquaculture-integrated agriculture systems, farm and water productivity are increased, fishpond water quality is improved, and the environmental impact of nutrient-rich water discharge, water costs, and the quantity of chemical fertilizer required for crops are all decreased. Even though aquaponics is widely used in Egypt, there is not much information available on aquaponics as an integrated farming system, and only a small amount of aquaculture water is used for crop irrigation since some researchers continue to underestimate its benefits on soil and water productivity [14,15]. Aquaculture water is currently used to irrigate many farms in recently fertilized soils, making it feasible to realize the value of irrigation with it. Therefore, it was necessary to conduct a realistic experiment to ascertain which types of aquaponics could be most useful in helping to address the food problem in Egypt as an alternative to conventional farming techniques. Due to the high price of aquaponics system installation and maintenance, this experiment was conducted using the Egyptian farmer aquaponics method to imitate the modern aquaponics system in an attempt to produce food and fish on a large scale under field conditions with little cost and dual-use of water as a scarce resource in Egypt.

Therefore, the current investigation aimed to investigate the impacts of aquaculture water used for irrigation on water productivity, soil quality, and watercress production as well as its applicability to sustainable farming methods under conditions of desert sandy soils. The following objectives of the current work were to accomplish this goal: (1) To evaluate catfish and tilapia aquaculture water quality for the irrigation of watercress. (2) To assess the impact of using aquaculture water for irrigation alone or in combination with various synthetic NPK fertilizers on watercress yield and quality characteristics. (3) To assess the impact of aquaculture water irrigation on some sandy soil quality parameters.

2. Materials and Methods

A watercress pot study was carried out to assess the effects of irrigation by catfish and tilapia aquaculture water on the examined sandy soil quality properties as well as the growth and yield parameters of watercress with various combinations of artificial NPK fertilizers. At the Faculty of Agriculture, Minia University, El-Minia Governorate of Egypt (28°18′16″ N latitude and 30°34′38″ E longitude), watercress pot experiments and aquaculture of catfish and tilapia were implemented. The following experimental techniques, materials, and research procedures were used in the current study:

2.1. Experimental Design, Procedures, and Treatments

The experimental design implemented was a complete randomized design (CRD) with 24 pots and three replicates (Table 1). The first factor was the irrigation type of water (catfish and tilapia); second factor was the artificial NPK fertilizer rate (0%, 25%, 50%, and 100%) of the levels that Ministry of Agriculture advised. Three replicates of catfish and then tilapia aquaculture samples of water were gathered prior to the start of the experimental procedures and sent for physicochemical analysis. The experimental design was summarized as shown in Table 1.

Table 1. Experimental design and treatments.

Treatments		**Replicates**		
		R1	**R2**	**R3**
Catfish Water (W1)	F0 (NPK 0%)	W1 F0	W1 F0	W1 F2
	F1 (NPK 25%)	W1 F0	W1 F1	W1 F3
	F1 (NPK 50%)	W1 F1	W1 F2	W1 F2
	F1 (NPK 75%)	W1 F1	W1 F3	W1 F3
Tilapia Water (W2)	F0 (NPK 0%)	W2 F0	W2 F0	W2 F2
	F1 (NPK 25%)	W2 F0	W2 F1	W2 F3
	F1 (NPK 50%)	W2 F1	W2 F2	W2 F2
	F1 (NPK 75%)	W2 F1	W2 F3	W2 F3

A total of 24 pots (30 cm diameters × 30 cm depth) were filled with 15 kg of sandy soil after air drying and sieved to a size of 2 mm. To create stable soil conditions, these pots were placed in the greenhouse at a temperature of 25 ± 10 °C and irrigated over three days with various fish farm waters at a rate of 60% of field capacity without filtering. After three days, watercress seedlings were planted in pots and watered with allotted water until harvest. To achieve high soil water percolation for the purpose of examining water quality parameters and determining whether the infiltrated water could be utilized again for fish farming, fish farm water was allotted while maintaining the soil moisture content above its water retention capacity by regular weight analyses and dropwise water applications.

2.2. Soil Properties Analyses

Physical and chemical characteristics of the experimental soil were analyzed before and after irrigation with aquaculture water to assure soil quality and to protect these sandy soils from salinity build-up and soil degradation. Consequently, soil samples were collected before and after irrigation with aquaculture water, then air dried, crushed, and sieved to pass through a 2.0 mm stainless steel sieve. Sieved soil samples were mixed thoroughly, and a subsample was taken for soil analyses using standard methods as explained by [16–19]. Some soil physicochemical properties before irrigation are illustrated in Table 2.

Table 2. Physical and chemical properties of the investigated sandy soil.

Soil Property	**Value**			
Particle size distribution %	Coarse sand 32.54	Fine sand 60.22	Silt 2.43	Clay 4.81
Soil texture	Sand			
Physical properties		Chemical properties		
Field capacity (F.C) %	17.75	Cation exchange capacity (CEC) $cmol_c\ kg^{-1}$		4.22
Permanent wilting point (PWP) %	4.78	Organic matter (OM) $g\ kg^{-1}$ *		4.67
Water holding capacity (WHC) %	19.88	Soil organic carbon (SOC) $g\ kg^{-1}$		2.68
AV.W (F.C–PWP) %	12.97	Electrical conductivity (EC) $dS\ m^{-1}$ at 25 °C		2.73
AV.W (WHC–PWP) %	15.10	Total N $g\ kg^{-1}$		0.24
Bulk density g/cm^3	1.64	C/N Ratio		11.17
Particle density g/cm^3	2.61	Total P $g\ kg^{-1}$		0.19
		Total K $g\ kg^{-1}$		3.22
		$CaCo_3^-$ $g\ kg^{-1}$		88.76
		pH (1–2.5 water)		8.41
		Total dissolved salts (TDS) mgL^{-1}		1747
Soluble Cations and Anions ($cmol_c/L$)				
Na^+		5.28		
Ca^{++}		14.65		
Mg^{++}		4.48		
K^+		2.28		
HCO_3		12.57		
Cl^-		5.59		
$SO_4^=$		7.47		
CO_3^{2-}		0.00		
Total counts of bacteria ($\times 10^4$ cfu/mL^{-1})		13		
Total phytoplankton (units $\times 10^4$/L)		Non		

Trace and heavy metals concentrations (mg kg^{-1})							
Fe	Mn	Zn	Cu	Ni	Pb	Cd	Cr
39.64	5.99	3.10	5.13	3.10	5.65	0.416	0.732

* Organic matter by loss on ignition method.

2.3. Fishponds Design and Experimental Materials

Earthen fishponds were established ten years ago for catfish and tilapia production in the nursery at the Faculty of Agriculture, Minia University. Watercress pot experiments were conducted in the agricultural greenhouse belonging to the soil department, 50 m away from fishponds. Irrigation water was transferred from the fishponds to irrigate the watercress experiment in the greenhouse and back again to the fishponds manually after soil percolation. Water was added to the fishponds to feed the system with additional tap water as needed to maintain overall levels if the infiltrated water from the watercress experiment was not sufficient to compensate.

At the beginning of the experiment, two cubic tanks were placed inside the main tilapia and catfish fishponds in the nursery to separate the experimental fish from the original farm in the nursery. The Nile tilapia fish unit consists of cubic tank (2 m^3) stocked with 100 Nile tilapia (*Oreochromis niloticus*) weighing 100 g $\pm$ 15 g representing intensive fish production. The North African catfish (*Pseudoplatystoma corruscans*) unit consists of cubic tank (2 m^3) stocked with 100 catfish weighing 300 g $\pm$ 35 g. Catfish and Nile tilapia were purchased alive after fishing directly from a local fisherman from the Nile. The fish were raised daily on poultry manure taken from the poultry farm at the Faculty of Agriculture, Minia University, using the equivalent of 2% of the weight of the fish. Aquariums were heavily aerated with air stones as the oxygen level rises and carbon dioxide is removed. Every three days, after the sludge at the bottom of the tank was disturbed and the solid portion of the wastewater was not purified for use as high-quality fertilizer, water was removed from the fishponds for watercress irrigation. In order to obtain filtered water for use in fish farming again, this water was subsequently used to irrigate watercress in the greenhouse utilizing the intensive flood irrigation method above the water holding capacity of the examined sandy soil.

2.4. General Methods and Analytical Procedures

In accordance with Avery et al. [18], Chapman et al. [19], Baird et al. [20], and the 23rd edition of Standard Methods for the Examination of Water and Wastewater [21], water and soil physical and chemical parameters were analyzed. According to the Standard Methods, the chemical oxygen demand (COD) and biological oxygen demand (BOD) were calculated [22]. A Shimadzu UV–VIS spectrophotometer was used (model UV-1201) to measure the content of the nutrient's ammonia ($NH_4{}^-N$), nitrate ($NO_3{}^-N$), and total phosphorus (TP). ICP-MS (Perkin Elmer NexION 300D) was used to assess total essential metals (Cu, Zn, Mn, and Fe) and non-essential elements (Ni, Cr, Cd, and Pb) in water and soil in accordance with [22,23].

The following list includes formulae used in the course of this experiment:

2.4.1. SAR, Sodium Adsorption Ratio

The following formula, which uses concentrations given in meq/L as reported in [24], is used to compute the sodium adsorption ratio (SAR).

$$SAR = \frac{Na^{+}}{\sqrt{\frac{Ca^{+2}+Mg^{+2}}{2}}}$$

2.4.2. RSC, Residual Sodium Carbonate

In accordance with Szabolcs and Darab [25], the following formula in meq/L was used to compute residual sodium carbonate (RSC).

$$RSC = \left(Hco_3^{-1} + Co_3^{-2}\right) - \left(Ca^{+2} + Mg^{+2}\right)$$

2.4.3. Magnesium Hazard Percentage

Calculating the magnesium hazard levels was completed using the following formula (in which the values are given in meq/L) [26,27].

$$Mgratio = \frac{Mg^{+2}}{(Ca^{+2} + Mg^{+2})} \times 100$$

2.4.4. Sodium Percentage

The proportion of sodium (Na%) is another parameter widely used to assess irrigation suitability of water quality [28]. The units of measurement for levels of ions are meq/L.

$$Na\% = \frac{\left(Na^{+1} + K^{+1}\right)}{\left(Ca^{+2} + Mg^{+2} + Na^{+1} + K^{+1}\right)} \times 100$$

2.5. Fishponds Water Properties Analyses

To assess the water's suitability for irrigating vegetables and forecast its effects on watercress growth and yield as well as some sandy soil quality properties under investigation, water samples from both aquaculture systems available for irrigation were collected and analyzed prior to irrigation. Water samples were collected in a clean, dry plastic bottle, filtered, and then either immediately analyzed or conserved in accordance with the recommendations of the American Public Health Association [21]. In the lab, pH, electrical conductivity (E.C), and total dissolved salt (TDS) characteristics of aquaculture water were analyzed. The basic metrics utilized to assess the quality of irrigation water were pH, soluble salt content (EC), primary soluble anions and cations, sodium adsorption ratio (SAR), Ca^{2+}/Mg^{2+} ratio, magnesium hazard (MH%), Na^+/Cl^- ratio, sodium percentage (Na%), and residual sodium carbonate (RSC). The parameters and chemical composition of water samples collected from fishponds before watercress was irrigated are shown in Table 3.

Table 3. Chemical composition and criteria of catfish and tilapia pondwaters used for watercress irrigation.

Chemical Composition and Criteria	Tilapia Pondwater	Catfish Pondwater
Chemical composition:		
pH (1–2.5 water)	7.4	7.8
Electrical conductivity E.C(ds m^{-1})	1.9	2.1
Total dissolved salts TDS (mgL^{-1})	1216	1344
Soluble cations:		
Soluble Ca^{2+} (meq/L)	7.65	8.63
Soluble Mg^{2+}(meq/L)	5.34	5.48
Soluble Na^{1+} (meq/L)	4.72	5.76
Soluble K^+ (meq/L)	1.48	2.12
Soluble anions:		
Soluble Cl^- (meq/L)	5.12	5.23
Soluble $SO_4{}^{2-}$ (meq/L)	8.45	11.55
Soluble $CO_3{}^{2-}$ (meq/L)	0	0
Soluble $HCO_3{}^-$ (meq/L)	5.35	4.57
Chemical criteria:		
Sodium adsorption ratio (SAR)	1.85	2.17
Ca^{2+}/Mg^{2+} Ratio	1.43	1.57
Magnesium Hazard (M.H%)	41.11	38.84
Na^+/Cl^- Ratio	0.92	1.1
Sodium percentage (Na^{1+}%)	32.16	35.83
Residual sodium carbonate (RSC)	<1.25	<1.25
COD (mg/L)	41	64
BOD (mg/L)	23	35
Total count of bacteria ($\times 10^4$ cfu /mL^{-1})	120	237
Total phytoplankton (units $\times 10^4$/L)	14,873	83,762

Concentration of macronutrients, micronutrients, and heavy metals in water

* $NH_4{}^-N$	* $NO_3{}^-N$	TP	Fe	Mn	Zn	Cu	Ni	Pb	Cd	Cr
Catfish (mg/L)										
2.94	13.24	2.86	1.65	0.98	0.66	0.67	0.55	0.34	0.01	0.01
Tilapia (mg/L)										
1.55	8.66	1.33	0.84	0.45	0.24	0.27	0.03	0.04	0.01	0.01

* Acceptable range for aquaculture by Egyptian law 84 of 1982 for $NH_4{}^-N$ = <0.5 and for $NO_3{}^-N$ = <45.

2.6. Watercress Yield and Quality Parameters

At the time of harvest (after 40 days from cultivation date), representative samples of vegetable plants were used to determine the following plant quality parameters of fresh and dry weight, TN concentration, and nitrate (mg kg^{-1} fresh weight). Dried and ground plant material was digested with sulfuric acid (H_2SO_4) and hydrogen peroxide (H_2O_2) using the Digestor (Buchi, speed digestor, model: K-425 Digestion unit). The amount of nitrogen in the plant digests was measured using the digested vegetable plant material and the Kjeldahl equipment (Buchi, model: 426 distillation unit), according to Baird [20] and AOAC [22] description.

2.7. Statistical Analysis

The obtained results were subjected to analysis of variance using the least significant difference (L.S.D.) test at 5% level of probability using the MSTAT-C v. 1.42 for completely randomized design (CRD) with three replicates. Significance of the differences was compared using least significant difference (LSD) at a 5% level of probability ($p < 0.05$)

3. Results and Discussion

The results of this integrated aquaponics trial are presented under evaluation of aquaculture water suitability for irrigation and its effects in turn alone or combined with different NPK fertilization rates upon some sandy soil quality properties, water quality for crop and fish irrigation after soil filtration, and watercress quality and productivity.

3.1. Evaluation of Catfish and Tilapia Aquaculture Water Quality for Irrigation of Watercress

In general, it is essential to assess the water's suitability for irrigation before utilizing catfish or tilapia fishponds' water to irrigate vegetables directly without treatment to prevent plant and soil degradation. Table 4 lists the chemical composition and criteria of irrigation water according to Ayers and Westcott [29].

Table 4. Guidelines for interpretations of water quality for irrigation.

Potential Irrigation Problem			**Degree of Restriction on Use**			
			Units	**None**	**Slight to Moderate**	**Severe**
Salinity (affects crop water availability)						
Electrical conductivity (EC_w) (or)			dS/m	<0.7	0.7–3.0	>3.0
Total dissolved salts (TDS)			mg/L	<450	450–2000	>2000
Infiltration (affects infiltration rate of water into the soil. Evaluate using EC_w and SAR together)						
Sodium adsorption ratio (SAR)	0–3	and EC_w		>0.7	0.7–0.2	<0.2
	3–6			>1.2	1.2–0.3	<0.3
	6–12			>1.9	1.9–0.5	<0.5
	12–20			>2.9	2.9–1.3	<1.3
	20–40			>5.0	5.0–2.9	<2.9
Specific Ion Toxicity (*affects sensitive crops*)						
Sodium (Na)						
Surface irrigation			SAR	<3	3–9	>9
Sprinkler irrigation			me/L	<3	>3	
Chloride (Cl)						
Surface irrigation			me/L	<4	4–10	>10
Sprinkler irrigation			me/L	<3	>3	
Boron (B)			mg/L	<0.7	0.7–3.0	>3.0
Miscellaneous Effects (affects susceptible crops)						
Nitrogen (NO_3^-N)			mg/L	<5	5–30	>30
Bicarbonate (HCO_3) (overhead sprinkling only)			me/L	<1.5	1.5–8.5	>8.5
pH				Normal range 6.5–8.4		

3.1.1. Effects of Aquaculture Water Used for Irrigation on Salinity Buildup of Sandy Soil

Table 5 compares the chemical composition and criteria of catfish and tilapia aquaculture waters used to irrigate watercress and then filtered by soil after irrigation. The total dissolved salts (TDS) ranged between 1216 (mg L) and 1344 (mg L) in the examined aquaculture waters before irrigation use, and the electrical conductivity ranged between 1.9 and 2.1 for tilapia and catfish pondwaters. Although these values are much higher than those of Nile water (TDS, 186 mg L or E.C, 0.258 dS m^{-1}) [28], it is suitable for crop irrigation. However, this saline water can be used with some caution in accordance with the FAO guidelines [28] for irrigation water.

Table 5. Average chemical composition and criteria of catfish and tilapia fish waters before and after soil filtration.

Water Chemical Composition and Criteria	Tilapia Pondwater		Catfish Pondwater	
Chemical composition				
	Before	After	Before	After
pH	7.4 a *	7.21 b	7.8 c	7.38 a
Electrical conductivity E.C (dS m^{-1})	1.9 a	0.49 b	2.1 a	0.51 b
Total dissolved salts TDS (mg L^{-1})	1216 a	313.6 b	1344 a	326.4 b
Soluble cations				
Soluble Ca^{2+} (meq/L)	7.65 a	0.78 b	8.63 a	0.82 b
Soluble Mg^{2+} (meq/L)	5.34 a	1.1 b	5.48 a	1.13 b
Soluble Na^{+} (meq/L)	4.72 a	3.38 a	5.76 a	3.45 a
Soluble K^{+} (meq/L)	1.48 a	0.1 b	2.12 c	0.1 b
Soluble anions				
Soluble Cl^{-} (meq/L)	5.12 a	1.4 b	5.23 a	1.7 b
Soluble $SO_4{}^{2-}$ (meq/L)	8.45 a	0.75 b	11.55 c	0.55 a
Soluble $CO_3{}^{2-}$ (meq/L)	0	0	0	0
Soluble $HCO_3{}^{-}$ (meq/L)	5.35 a	3.12 b	4.57 a	3.25 a
Chemical criteria				
Sodium adsorption ratio (SAR) %	1.85 a	2.81 b	2.17 a	2.89 b
Ca^{2+}/Mg^{2+} Ratio	1.43 a	0.71 b	1.57 a	0.73 b
Magnesium hazard (M.H%)	41.11 a	41.49 a	38.84 a	42.05 a
Na^{+}/Cl^{-} Ratio	0.92 a	2.41 b	1.10 a	2.03 b
Sodium percentage (Na^{1+}%)	32.16 a	64.92 b	35.83 a	64.54 b
Residual sodium carbonate (RSC) meq L	<1.25	<1.25	<1.25	<1.25
COD (mg/L)	41 a	43.25 bc	64 c	49.75 b
BOD (mg/L)	23 a	25.75 b	35 b	35.5 a
Total counts of bacteria ($\times 10^4$ cfu/mL^{-1})	120 a	10,5 c	237 b	13.5 c
Total phytoplankton (units $\times 10^4$/L)	14,873 a	186.75 c	83,762 b	490.5 d

* Figures followed by the same letters through entire rows are insignificantly different at <5% probability level.

The chemical analyses of filtered water after irrigation results from Table 5 indicated that there were significantly lower amounts of calcium, magnesium, and potassium than sodium in the investigated water samples due to sandy soil-specific filtration, indicating the importance of aquaculture water as a source of these essential plant nutrients. On the other hand, due to a significant increase in Na rather than other cations in water samples, water SAR increased significantly from 1.85 to 2.81% for tilapia water and from 2.17 to 2.89% for catfish water before and after irrigation, respectively. Also, soluble anions were significantly lowered in water samples after soil filtration except for HCO_3 ion. Results of EC and TDS studies show that the observed values at both aquaculture waters after soil filtering did not exceed the EG law 48/1982 limit of 500 mg/L, although the measured values at both aquaculture waters prior to soil irrigation did not exceed the FAO limit of 2000 (mg/L).

Salts will build up in the soil because of routinely applied fish farming waters, albeit they usually do so at a higher concentration when used to irrigate with catfish water rather than tilapia. Since the studied soil's saturated extract electrical conductivity

(ECe = 2.73 dS m^{-1}) is less than 4 dS m^{-1}, it is classified as "non-saline". As the salinity of the water increases, more caution must be taken to remove salts from the root zone before they accumulate to a concentration that could affect yields.

3.1.2. Impacts of Aquaculture Water Used for Irrigation on Soil Infiltration

Both aquaculture waters met the criteria for "None" degree usage restrictions (Table 4) in terms of SAR and EC values; this demonstrates that employing these aquaculture waters for irrigation in the investigated sandy soil may not provide an infiltration problem [29–32]. When SAR and EC_w are used to assess a potential soil infiltration rate issue, the soil infiltration rate often increases with increasing water salinity and decreases with either lowering salinity or rising sodium content with respect to calcium and magnesium [29,32].

3.1.3. Toxicity of Certain Ions in Aquaculture Irrigation Water

The aquaculture water used in the study had a sodium absorption ratio that was less than 3.0, which suggests that it may not ultimately cause sodium toxicity problems when used to irrigate vegetables. According to FAO [28] and Ayres and Westcott [29], the use of such water for the irrigation of vegetables may lead to an increased chloride toxicity problem. Regarding the issue of chloride toxicity in relation to irrigation water quality, each of the aquaculture waters had a chloride concentration between 4.0 and 10.0 meq L^{-1}, which is of "slight to moderate" restriction. The water of tilapia aquaculture under study has Na/Cl ratios less than one (0.92), implying that the water content of chloride is higher than that of sodium, while the water of catfish has Na/Cl ratios higher than one (1.10), implying the little water content of chloride.

Catfish or tilapia aquaculture pond water samples often had low concentrations of sodium and chloride (catfish Na^+ = 5.76, Cl^- = 5.23 and tilapia Na^+ = 4.72, Cl^- = 5.12 meq L^{-1}), which suggests that sodium and chloride had little impact. Leaf burning and dead tissue around the outer edges of the leaves are the typical signs of sodium poisoning, but the symptoms of chloride toxicity first emerge at the distal tip of the leaves and are therefore more challenging to diagnose [31]. Chloride content is essential for identifying whether water is acceptable for irrigation since chloride ions are harmful and most plants are particularly sensitive to chloride in irrigation water [32–34]. Bicarbonate concentrations in both aquaculture waters ranged from 1.5 to 8.5 meq L^{-1} (Table 4), which falls under the category of "Slight to Moderate" use restrictions. As a result, utilizing this water to irrigate crops may cause white scale issues on plants or fruits during spray irrigation or block emitters when using drip irrigation [32,33]. The irrigation technique being utilized will determine the management decisions to be made to prevent a deposit issue.

3.1.4. Hydrogen Ion Activity in Irrigation Water (Water pH)

This study's findings showed that the pH of catfish water significantly reduced from 7.80 to 7.38 immediately following soil filtrations, but the pH of tilapia water insignificantly decreased from 7.40 to 7.21 immediately following soil filtrations (Table 4). The pH of catfish water with soil filtering was lower by up to 0.42 pH units when compared to tilapia-filtrated water. The primary function of water pH, according to Abd El-Azeim et al. [33] and FAO [28], is to identify abnormal water that may cause a nutritional imbalance or contain toxic ions and, as a result, requires additional examination. The soil filtration process can significantly change the pH of the drainage water following each irrigation cycle. The hydrogen ion activity (water pH) values of both fish farming waters were in the normal range (6.5 to 8.4) for irrigation, indicating that utilizing such water to irrigate plants unlikely results in a temporary change in the pH of the soil or a nutritional imbalance. A range of 6.0 to 8.5 is ideal for the majority of organisms and crops, according to FAO [28] and Egyptian Law 48; moreover, these results show that the pH levels for both aquaculture waters utilized for irrigation are within this range.

3.1.5. Relationship between Calcium/Magnesium Ratio and Irrigation Water Quality

The Ca/Mg ratio in both fish farming waters used for irrigation (tilapia = 1.43 and catfish 1.57) was greater than 1.0, suggesting that using these waters for watercress irrigation may neither cause a calcium deficiency issue or a problem with sandy soil infiltration. Lower Ca/Mg ratios considerably promote the development of sodic soils in sandy soils [31]. It is essential to assess the water source's quality and determine whether it is adequate for plant irrigation before problems with irrigation water quality arise. The irrigation water's Ca^{++}, Mg^{++}, and Na^{+} contents must also be evaluated to establish whether it is appropriate for irrigation.

In relation to the magnesium hazard index (%), examined aquaculture waters drawn from tilapia and catfish ponds vary from 38.84 to 41.11, making them suitable for crop irrigation. High Mg^{2+} concentrations in irrigation water produce an increase in exchangeable Na^{+} in irrigated soils, boosting the magnesium hazard index, which may damage soil structure and decrease crop nutrient uptake by increasing soil alkalinity. Water with a magnesium hazard of more than 50% is recognized as being inappropriate and extremely dangerous for the majority of farmed soils [31,33].

The results of the study suggested that issues with deterioration or infiltration in the examined sandy soil may not be caused by variables affecting water quality for irrigation, such as total cations and anions, magnesium risk, sodium adsorption ratio (SAR), pH, relative percentages of sodium and bicarbonate concentrations as associated with chloride, calcium, and magnesium concentrations. Furthermore, our results indicated that using catfish or tilapia aquaculture waters for irrigation can eventually cause salt concerns in the investigated sandy soil if not carefully monitored and managed with top-notch extension programmers. Therefore, there should be a focus on future sustainable irrigation management and the use of aquaculture water for crop irrigation in integrated aquaponic farming systems.

In contrast, results of soil-filtered water analyses after intensive surface irrigation indicated that this water may not cause adverse environmental effects or deterioration or infiltration issues in the examined sandy soils. Also, chemical analysis of soil-filtered water showed higher water quality in terms of water suitability parameters and criteria than in aquaculture waters for both catfish and tilapia, indicating high suitability for irrigation of crops or fish again despite soil fertilization with different NPK rates (0%, 25%, 50%, 100%).

3.1.6. Dissolved Oxygen (DO), Chemical and Biological Oxygen Dissolved (COD and (BOD) in Relation to Irrigation Water Quality

Table 6 shows chemical oxygen dissolved (COD) and biological oxygen dissolved (BOD) (mg/L) levels recorded in different aquaculture waters for catfish and tilapia before irrigation and after filtration by sandy soil under investigation. COD average values range between 41 before irrigation to 57 (mg/L) after soil filtration for tilapia aquaculture pond water, while these values range between 64 and 50 mg/L for catfish aquaculture pond water. BOD average values for tilapia aquaculture pond water range between 23 before irrigation and 40 (mg/L) after soil filtration, while these values range between 35 and 25 mg/L for catfish aquaculture pond water. The greater mobile activity of catfish, which increases the oxygen content, may be the cause of the higher COD and BOD concentrations in the irrigation water taken from the catfish farm before watercress irrigation as compared to the irrigation water after soil percolation.

Measuring water quality before and after irrigation, COD or BOD levels are higher than those required by EG Law 48/1982 and FAO [28] for the irrigation of fish and crops. The catfish and tilapia aquaculture water are safe to use for irrigating vegetables and can be utilized for irrigating fish once more after soil filtering, according to the COD and BOD values. The amount of oxygen that is freely available for living things in water is known as dissolved oxygen (DO), and values below 5 mg/L are stressful for the majority of aquatic creatures. DO levels below 2 or 1 mg/L will not support fish to live, and ranges from 0 in bad water conditions to a high of 25 mg/L in very healthy water [26].

The amount of dissolved oxygen in water indicates the possibility for flora and fauna to exist in the water system, and the amount of oxygen needed changes depending on the species and stage of life. Natural water bodies' oxygen content changes according to factors including temperature, salinity, turbulence, and the algae and plant activity that perform photosynthetic reactions.

According to Mahmoud et al. [34] and El-Sayed [35], BOD quantifies the amount of oxygen utilized by microbes to oxidize organic materials. According to this research finding, catfish and tilapia pondwaters differ significantly from one another. The water in tilapia ponds had a minimum value of 26 mg/L, whereas the water in catfish ponds had a maximum value of 77 mg/L. These differences were due to the discharge of catfish excreta that had been extensively polluted and the high activity of catfish that were feeding on poultry manures. BOD and COD had a positive correlation (r = 0.88; n = 24; p = 0.05). In an aquaculture system, COD is the total amount of oxygen needed to thoroughly oxidize all organic matter into CO_2 and H_2O, which are effective markers of water pollution [34–36]. Similar to BOD, the COD in the catfish pond water increased, which was ascribed to the higher activity of catfish. Overall, the findings of this study showed that the COD and BOD levels in both fishpond waters regarding water quality for fish or vegetable irrigation may not result in concerns with quality deterioration for fish and vegetables.

3.1.7. Water Microbial and Phytoplankton Status in Relation to Water Quality for Irrigation

Table 6 displays the total counts of bacteria and phytoplankton. Results showed that there were significant average changes in the total bacterial counts in tilapia and catfish waters, which varied from 120 to 237 ($\times 10^4$ cfu/mL), respectively. In contrast, the total bacterial count in soil-filtered water varied from 6 to 13 ($\times 10^4$ cfu/mL) for tilapia waters and from 11 to 16 ($\times 10^4$ cfu/mL) for catfish waters (Table 5). Due to significant contamination from the species of fish, catfish pond water had the highest levels of bacterial total counts. The likelihood of the infection of irrigated fish or crops is raised by the presence of numerous bacteria, particularly pathogenic bacteria, in the water [34].

These quantities in both aquaculture environments were over the World Health Organization's allowable limits for fish farming, and the findings completely confirm those of [30,33]. Monitoring the presence of microorganisms dangerous to people and identifying bacterial species that may be transmitted to irrigated fish or crops, which may represent dangers to human health, are major goals of bacteriological investigations of water used to irrigate crops or fish. The quality of irrigated fish, aquatic species, vegetation, and ultimately human health are all protected through monitoring [34,37].

Table 6. Microbial and biochemical status of water samples filtered by sandy soil irrigated with aquaculture water.

Treatment	COD	BOD	Total Count of Bacteria	Total Count of Phytoplankton
	mg L^{-1}	mg L^{-1}	$\times 10^4$ cfu/mL	Units $\times$ 10^4/L
$W_1(F_0)_{0.0\%}$	47	35	11	324
$W_1(F_1)_{25\%}$	52	30	14	386
$W_1(F_2)_{50\%}$	46	38	16	267
$W_1(F3)_{100\%}$	54	39	13	385
$W_2(F_0)_{0.0\%}$	46	31	11	210
$W_2(F_1)_{25\%}$	42	22	12	133
$W_2(F_2)_{50\%}$	44	26	13	215
$W_2(F_3)_{100\%}$	41	24	6	189
$LSD_{0.05}$	7.63	8.33	1.12	12.23

cfu: colony forming unit.

Catfish aquaculture water had the greatest phytoplankton concentration, where the fish farms were fed with poultry manure twice daily (83,762 units $\times$ 10^4/L). Increased levels of nitrogen and phosphorus concentrations as well as the organic load from poultry manure as a source of nutrition are to blame for the significant growth in phytoplankton in catfish ponds. The minimum number of phytoplankton existed in tilapia aquaculture water, recorded at 14,873 units $\times 10^4$/L, which may be attributed to the abundance of nutrients from poultry manures and water stagnation. Phytoplankton are microscopic single-celled plants sometimes referred to as microalgae that live in both freshwater and saltwater habitats. Phytoplankton forms the base of the aquatic food chain, providing sustenance for a wide variety of marine life, such as fish, shellfish, and even whales. These microscopic plants are essential producers in marine ecosystems, storing excess carbon dioxide and providing an important food source for countless species [38,39].

As the primary producers of the aquatic environment and the foundation of the food chain, phytoplankton unquestionably have a significant impact on aquatic ecosystems and are crucial for nutrient cycling and energy conversion [34]. Temperature, light, and nutrients are significant elements determining the success of the phytoplankton community in aquaculture [34,40]. The study of phytoplankton community succession is of significant theoretical and practical value as phytoplankton (Microalgae) biomass is widely used in a variety of industries. Because of the negative consequences of chemical fertilizers, biofertilizers are needed to protect the soil, plants, and ecosystem. In agriculture, where it is used as a biofertilizer, it can play a crucial role because it can fix atmospheric nitrogen and turn it into ammonia for plant growth and soil stabilization [41].

Because of the negative consequences of chemical fertilizers, bio-fertilizers are needed to protect the soil, plants, and ecosystem. Since it can fix atmospheric nitrogen and turn it into ammonia for plant growth and soil stabilization, phytoplankton (microalgae) biomass can play a particularly crucial function in agriculture where it is utilized as a biofertilizer [41]. A novel and environmentally friendly strategy to promote plant growth while benefiting agricultural ecosystems and nature is to use phytoplankton as a source of soil fertilizer [39,42]. By properly using phytoplankton fertilizer in agricultural systems, although excess use of conventional fertilizers can cause unwanted algal blooms in waterways, using phytoplankton as fertilizer is an emerging trend that may be more environmentally friendly. In addition, phytoplankton fertilizer may provide a rapid and efficient nutrient delivery system to plants, due to the nanoparticle size and high levels of bioavailability that are easily absorbed by plants. The wide range of nutrients found in phytoplankton, including essential vitamins, NPK, minerals, amino acids, and trace elements, can help promote healthy root growth and overall plant vigor [39,42,43].

3.1.8. Relationship between Water Quality for Irrigation, Macro- and Micronutrient Levels, and Heavy Metal Concentration

Table 7 displays the average concentrations of macro- and micronutrients, as well as heavy metals, in both waters used to irrigate watercress plants during both growth seasons. By measuring the content of macro- and micronutrients as well as heavy metals, this study analyzed and monitored the water quality in terms of nutrition and pollution status of both aquaculture waters of catfish and tilapia used for watercress irrigation. The temporal distributions of most parameters showed significant changes. The findings of this study demonstrated high levels of water pollution as a result of the increase in ammonia, nitrate, total phosphorus, and iron contents in the case of catfish aquaculture water, as well as substantial changes in temporal distributions of most of the parameters.

Due to the usage of poultry manure as a feed source in aquaculture systems, the nutrients are present in aquaculture water, indicating the high nutritional status of both aquaculture waters for crop irrigation. With concentrations of roughly 8.66 to 13.24 mg/L of nitrogen nitrate and 2.94 to 1.55 mg/L of nitrogen ammonia for catfish aquaculture water and tilapia, respectively, average nitrate ($NO_3{}^-N$) and ammonium ($NH_4{}^-N$) displays considerable and extensive regional variability over both aquaculture waters. Phosphorus shows the same direction and was generally around 2.86 mg P/L for catfish aquaculture water and 1.33 mg P/L for tilapia. After soil filtration for irrigation water, all macro- and micronutrients were under detection limits (UND) except for nitrate in water samples percolated from sandy soil under investigation. At all investigated treatments, only nitrates were present in the soil-filtered water of both catfish and tilapia water after soil filtration indicating that nitrates can leach into water resources causing pollution.

Table 7. Average water macro- and micronutrients and heavy metals concentration of catfish and tilapia fish farming waters before and after soil filtration.

Water Nutritional and Pollution Status	Tilapia Water		Catfish Water	
	(mg L^{-1})			
	Before	After	Before	After
NH_4^-N	1.55 a *	0	2.94 b	0
NO_3^-N	8.66 b	1.86 d	13.24 a	3.24 c
Total phosphorus (TP)	1.33 b	UDL **	2.86 a	UDL
Iron (Fe)	0.84 b	UDL	1.65 a	UDL
Manganese (Mn)	0.45 b	UDL	0.98 a	UDL
Zink (Zn)	0.24 b	UDL	0.66 a	UDL
Cupper (Cu)	0.27 b	UDL	0.67 a	UDL
Nickel (Ni)	0.03 b	UDL	0.55 a	UDL
Lead (Pb)	0.04 b	UDL	0.34 a	UDL
Cadmium (Cd)	0.01 a	UDL	0.01 a	UDL
Chromium (Cr)	0.01 a	UDL	0.01 a	UDL

* Figures followed by the same letters through entire rows are insignificantly different at <5% probability level; ** UDL: under detection limits.

Aquaculture water typically contains major and minor metals as a result of contaminants in poultry faces, sediments, or air pollution. The results showed that the average concentrations of cadmium and chromium in tilapia and catfish aquaculture waters were around 0.01 mg/L, with negligible fluctuations before irrigation use and distinct patterns in water samples after soil filtration, where Cd and Cr were below detection limits. While the average levels of Fe, Mn, Zn, and copper concentrations were all within legal limits for irrigation, the results also showed that catfish and tilapia aquaculture waters differed significantly before irrigation. These levels in soil-filtered water samples were below the detection limit (UDL). The iron levels in the water used to raise tilapia and catfish were, respectively, 0.84 mg/L and 1.65 mg/L. With the exception of iron in catfish water, for which the EG Law 48/1982 and FAO recommend a threshold of 1.00 mg/L, these amounts of contaminants are typically not restricted to direct irrigation usage.

3.2. Impacts of Aquaculture Water Irrigation on Various Soil Quality Indicators

Following both watercress growth seasons, Table 8 displays the effects of aquaculture water irrigation on a few sand soil quality parameters. After both growth seasons, the results showed that soil electrical conductivity and total dissolved salts had significantly decreased. This decline throughout both seasons may be related to heavy irrigation using aquaculture waters with lower electrical conductivity values. Higher crop yields will come from adding less salt to the researched soils with each subsequent intense irrigation event. This is especially true for the sandy soil under study where internal drainage and infiltration are prevalent. For the effective management of irrigated soils in an integrated aquaponics system employing the Egyptian farmer's technique, ongoing thorough soil studies are crucial.

Based on the salinity of the water used, the soil salt buildup will begin to balance after a number of continuous irrigations with aquaculture waters. All irrigation water contains salts, and as the water evaporates, the salts accumulate in the soil profile. In order to prevent this concentration from reducing crop yield, the salts must be moved below the root zone [30,31]. One of the primary factors contributing to Egypt's saline soil formation is the use of saline water as the only source of irrigation, particularly in arid regions. Saline irrigation can cause soil salinity to accumulate in the root zone throughout growing seasons, after harvest, and over time [34,44]. Soil drainage is hindered by insufficient applied irrigation. These results demonstrate the importance of preserving soil properties and vegetable yield production while using long-term aquaculture water for irrigation in dry situations.

Table 8. Some sandy soil quality parameters as affected by irrigation with catfish and tilapia aquaculture waters before and after soil filtration.

Soil Quality Parameters	Soil Irrigated with Tilapia Water		Soil Irrigated with Catfish Water	
Chemical criteria:				
	Before	After	Before	After
pH (1–2.5)	8.41 a *	8.11 b	8.41 a	8.21 b
Electrical conductivity EC (dS m^{-1})	2.73 a	2.33 b	2.73 a	2.39 b
Total dissolved salts TDS (mg L^{-1})	1747 a	1491 b	1747 a	1529 b
Soil soluble anions				
Soluble Ca^{2+} (meq/L)	14.65 a	15.45 a	14.65 a	16.22 a
Soluble Mg^{2+} (meq/L)	4.48 a	5.66 a	4.48 a	6.08 a
Soluble Na^{+} (meq/L)	5.28 a	5.11 a	5.28 a	5.08 a
Soluble K^{+} (meq/L)	2.28 a	2.76 a	2.28 a	2.77 a
Soil soluble cations				
Soluble Cl^{-} (meq/L)	5.59 a	4.99 a	5.59 a	5.11 a
Soluble $SO_4{}^{2-}$ (meq/L)	7.47 a	8.66 a	7.47 a	9.33 a
Soluble $CO_3{}^{2-}$ (meq/L)	0	0	0	0
Soluble $HCO_3{}^{-}$ (meq/L)	12.57 a	11.56 a	12.57 a	11.89 a
Trace and heavy metals concentrations (mg kg^{-1})				
Fe	39.64 a	40.11 a	39.64 a	41.22 a
Mn	5.99	6.23 a	5.99 a	6.11 a
Zn	3.10 a	2.99 a	3.10 a	2.81 a
Cu	5.13 a	4.88 a	5.13 a	4.95 a
Ni	3.1	3.44	3.1	3.65 a
Pb	5.65 a	5.61 a	5.65 a	5.76 a
Cd	0.416 a	0.523 a	0.416 a	0.502 a
Cr	0.732 a	0.755 a	0.732 a	0.776 a
Total counts of bacteria ($\times 10^4$ cfu/mL^{-1})	13 a	123 b	13 a	156 c
Total phytoplankton (units $\times$ 10^4/L)	Non	576 a	Non	1264 b

* Figures followed by the same letters through entire rows are insignificantly different at <5% probability level.

The results of Table 8 show that throughout the course of two growing seasons, aquaculture water was used to water the watercress, which resulted in a significant reduction in the amount of aqueous hydrogen activity (pH). However, any change in soil pH caused by aquaculture water will probably occur gradually because the soil is strongly buffered and resistant to pH changes [26]. This slight decrease in soil pH after two watercress growing seasons was significant ($p < 0.05$). According to Mosa et al. [45], bringing the soil into the right pH range should be the first step in any fertilizer or irrigation management scheme. The pH of the soil has a big impact on plant growth, nutrient availability, and the activities of soil microorganisms and enzymes. Maintaining the proper pH of the soil is essential for growing vegetables [46,47].

Table 8 shows how different soluble cations and anions in sandy soil were impacted by aquaculture irrigation water after two growth seasons. When comparing the concentration of anions and the findings of the dissolved cations in the soil before and after irrigation with aquaculture water, the concentrations in the soil increased barely after both seasons. The frequent irrigation with aquaculture water rich in these cations and anions up until equilibrium is reached can be responsible for these minor increases. Changes in the amount of soil cations and anions can be attributed to precipitation or the dissolution of soil minerals, which increases the amount of their ions in the soil–water matrix.

The results of irrigation with aquaculture water on the levels of heavy and trace metals in sandy soil during both watercress growing seasons are shown in Table 8. The findings demonstrated that there was little difference between both growth seasons in the concentration of heavy metals in the soil. Results showed that the mean concentration values of all heavy and trace metals in the sandy soil under evaluation increased somewhat but remained within acceptable ranges and tolerable levels following two seasons of irrigation with aquaculture water. Heavy metal contamination of soil or water, particularly with nickel, chromium, lead, and cadmium, is of particular concern, NO_3^-N, NH_4^+N, Cu, Fe, Mn, and Zn are additional elements that can be poisonous to plants at greater concentrations but are also phytonutrients [48].

Soil total counts of bacteria and phytoplankton after irrigation with aquaculture water of tilapia and catfish for two seasons are shown in Table 8. The microbial and enzymatic activity of soils used for crop production is important in the phyto-availability of soil nutrients. The minimum total number of bacteria existed in sandy soil before irrigation with aquaculture waters, recorded at 13×10^4 cfu/mL indicating little microbial activity in sandy soils. The highest total counts of bacteria and phytoplankton were recorded in soils irrigated with catfish aquaculture water (576×10^4 cfu/mL and 1264 units $\times 10^4$/L) due to the high content of aquaculture water of catfish with bacteria and phytoplankton compared to tilapia water.

Catfish and tilapia aquaculture water used for vegetable irrigation contains high contents of bacteria and phytoplankton and enough nitrogen and phosphorus to support the growth and quality of watercress plants. Since then, both aquaculture waters have been categorized as eutrophic–hypertrophic water bodies, receiving significant nitrogenous and phosphorus inputs from the feeding of poultry manure in addition to rising phytoplankton (algae) levels [34]. According to this study's findings, using microbial- and phytoplankton-rich aquaculture water to irrigate crops and as a soil fertilizer in sandy soils under investigation in place of partially synthetic fertilizers can help maintain a balanced soil ecosystem while allowing for the growth of healthy and plentiful crops [39,40]. Unlike synthetic fertilizers derived from petrochemicals and mineral extracts, which may contain harmful chemicals or pollutants, using aquaculture water rich in phytoplankton provides a safer partial fertilizer made entirely of organic matter [41].

3.3. Impacts of Aquaculture Water Irrigation on Watercress Yield Quality

3.3.1. Watercress Nutritional Status and Development Characteristics

Table 9 for tilapia, catfish, and all NPK treatments displays the effects of irrigation with aquaculture water on fresh weight (g/pot), dry weight (g/pot), plant uptake (g/pot), and nitrogen concentration% of watercress plants over the course of two seasons. The growth, production, and nutritional quality of watercress were significantly affected by irrigation with either aquaculture water alone (control) or irrigation with various rates of NPK inorganic fertilizers, according to statistical analysis of the data in Table 8. Results showed that the addition of artificial NPK fertilizer significantly increased the growth characteristics of watercress plants when compared to the control, regardless of application rates or type of aquaculture water.

According to growth characteristics (fresh and dry weights) and total N uptake of watercress plants at all NPK application rates, watercress grown in pots at 25% of the required levels and watered with catfish aquaculture water produced significant and high quality and quantity. A benefit of integrating irrigation with aquaculture water and inorganic NPK fertilizers was improved soil structure, which promoted efficient plant root flowering. The final effect was an increase in soil microbial activity, which improved the health of sandy soils [47,48]. This conclusion agrees with those of [49–52].

Based on the application rates of NPK fertilizers, statistical analyses revealed that there were occasionally statistically significant variations in the nutritional and growth characteristics of watercress plants ($p \leq 0.05$; Table 9). The crop yield was unaffected by the addition of more than 25% of the recommended NPK levels, and the drop in yield was not accompanied by an increase in the application of inorganic NPK fertilizers. Among the aquaculture water used for irrigation in both seasons, the nutritional quality and growth metrics of watercress plants watered with catfish aquaculture water were significantly higher than those irrigated with tilapia water. In conclusion, the varied impacts related to irrigation water type can be explained by differences in the soil microbial activities brought about by each kind of aquaculture water. Additionally, the findings demonstrated that there were no significant seasonal variations in the nutritional and growth characteristics of the watercress.

Table 9. Watercress growth and nutrition parameters as affected by irrigation with fish farming water and different NPK fertilizer treatments.

Treatment		Fresh Weight (g/pot)		Dry Weight (g/pot)		Nitrogen Uptake (g/pot)		N Concentration %	
Irrigation Method and Fertilizer Rates		Season 1	Season 2	Season 1	Season 2	Season 1	Season 2	Season 1	Season 2
* W_1	$(F0)_{0\%}$	224.57	225.33	21.78	21.95	0.0215	0.0223	0.99	1.02
	$(F1)_{25\%}$	282.85	281.45	29.95	29.75	0.0913	0.0940	3.05	3.16
	$(F2)_{50\%}$	287.12	286.15	30.65	30.55	0.1220	0.0965	3.98	3.16
	$(F3)_{100\%}$	286.84	286.59	30.14	30.09	0.0871	0.0767	2.89	2.55
** W_2	$(F0)_{0\%}$	154.72	155.11	15.73	15.85	0.0158	0.0177	1.01	1.12
	$(F1)_{25\%}$	163.77	164.65	17.87	18.12	0.0336	0.0357	1.88	1.97
	$(F2)_{50\%}$	166.12	165.85	18.88	18.54	0.0457	0.0380	2.42	2.05
	$(F3)_{100\%}$	169.46	168.57	19.18	19.22	0.0529	0.0473	2.76	2.46
$LSD_{0.05}$	Irrigation water	14.39	14.47	0.65	1.76	0.021	0.013	0.415	0.423
	Rate	3.94	3.93	0.48	1.57	0.042	0.016	0.524	0.518

* W_1 Catfish farming water, ** W_2 Tilapia fish farming water.

Table 9 shows how various researched treatments affected the total N intake of watercress plants over the course of two seasons. The majority of the time, there was no discernible increase in total nitrogen uptake at application rates higher than 25% of the NPK levels that are advised. This finding suggests that, as a result of aquaculture water irrigation, diminishing returns to nitrogen uptake are scaled to increase application rates above 25% of the NPK levels. This means that excess N may accumulate in sandy soils or flow into groundwater, and watercress plants may have consumed more N than they should have. For synthetic fertilizer application to be more successful at a certain crop level, residual soil NO_3^-N must be reduced [2].

3.3.2. Watercress Plants N% Concentrations

Nitrogen contents in the leaves of watercress plants grown on inorganic NPK fertilized pots were about two times greater than those of plants grown on control plots (irrigated with aquaculture water alone) in the case of the lowest fertilizer application rate of 25%. N concentrations of watercress plants generally increased significantly with increasing application rates of inorganic NPK fertilizer while being watered with aquaculture water in both seasons, compared to using aquaculture water for irrigation alone.

Data indicated that irrigation with catfish aquaculture water significantly increased watercress N concentration more than irrigation with tilapia water, whether used alone or in conjunction with inorganic NPK fertilizers. The significant increase may be due to the nutritional differences between the two aquaculture waters under examination. The average percentage of nitrogen concentrations was all within the ideal range (1.2–4.0), with the exception of the lowest rate of watercress cultivated in sandy soil and irrigated with aquaculture water without inorganic fertilizers, which was barely below this range [53].

3.3.3. Impacts of the Investigated Treatments on Nitrate Pollution of Watercress Plants

Levels of nitrate in watercress (mg/kg fresh weight) from all pots treated with fertilizer were substantially affected by the addition of inorganic NPK fertilizers ($p \leq 0.05$) when compared to the control (Table 10). Additionally, watercress plants grown on NPK-fertilized pots and watered with catfish aquaculture water had nitrate contents significantly greater than those of the NPK-fertilized pots watered with tilapia water in both seasons. The statistical analyses reveal that the kind of irrigation water and the rates of fertilizer NPK application do affect the nitrate contents in watercress plants in a significant way. Since people ingest more than 80% of all nitrates through vegetables, the primary source of nitrate contamination in the food chain is vegetables.

Table 10. Effects of irrigation water and different NPK fertilizer treatments on watercress nitrate contents mg kg^{-1} fresh weight.

Treatment		Nitrate Concentration (mg kg^{-1} Fresh Weight)	
		Season 1	**Season 2**
* W_1	$(F0)_{0\%}$	1386	1399
	$(F1)_{25\%}$	1406	1718
	$(F2)_{50\%}$	1637	1811
	$(F3)_{100\%}$	1815	2101
** W_2	$(F0)_{0\%}$	1016	1111
	$(F1)_{25\%}$	1162	1215
	$(F2)_{50\%}$	1215	1212
	$(F3)_{100\%}$	1326	1295
$LSD_{0.05}$	Irrigation water	54.22	74.32
	Fertilizer rates	60.19	65.78

* W_1 catfish farming water, ** W_2 tilapia fish farming water.

Nitrate contents in watercress plants were often lower than those mandated by the European Commission for leafy and tuber vegetables (max 2500 mg nitrate kg/fresh weight), according to [54]. The acceptable daily intake (ADI) for nitrate was established by the European Food Safety Authority (EFSA) in 2008 and the EU Scientific Committee for Food in 1995, respectively, at 3.7 mg of nitrate per kg/m of body weight. When watercress plants were fertilized with high rates of inorganic NPK fertilizer and irrigated with aquaculture water, huge amounts of nitrate accumulated in the plants. Nitrate poses serious health hazards when consumed in large amounts by humans.

Vegetables can contain anything between 1 and 10,000 mg kg of nitrate [55]. These research conclusions demonstrated that, in the second season, at the highest application rates of 100% of the NPK recommended levels and watered with aquaculture catfish water, all samples of watercress had nitrate concentrations below 2000 mg kg^{-1} and just one sample over 2000 mg kg^{-1}. However, the mean nitrate concentration in almost all plant samples was significantly below the permitted maximum of 1500 mg kg^{-1}. Vegetables become contaminated with nitrate when plants absorb more than is necessary for healthy growth. On the one hand, vegetables with a tendency to nitrate accumulation include watercress. On the other side, nitrates are infrequently accumulated in vegetables like carrots, French beans, peas, and cauliflower. These findings demonstrate that plants like watercress can absorb soil nitrogen that is still present and prevent leaching and N losses during fallow periods [55].

4. Conclusions

Due to Egypt's current water shortage, improving water productivity through dual water use in an integrated aquaponic farming system is the most important outcome of on-farm water management interventions. This will also enhance crop and fish yields and quality, as well as mitigate negative environmental effects. Aquaponics in its modern style and inputs is still not widespread in rural Egypt, although it was carried out by Egyptian farmers in its own style on a large scale long ago without knowing what they were doing. This is to some extent because today's modern aquaponic systems require significant capital, operating, and maintenance expenses. It is necessary to find innovative and cheap aquaponic techniques. This study contributes in a positive way to facing the challenge by evaluating the implementation of the integrated crop and fish farming system invented by Egyptian farmers. It will be an effective alternative to modern aquaponic plant and fish farming techniques with double water use with higher crop yields. This research finding suggested that the integrated aquaponic invented by the Egyptian farmer is a farming method that is environmentally feasible because it has had a favorable effect on soil characteristics, crop and water productivity, and the environment. The various integrated aquaponic systems for sustainable agriculture still need to be better understood; hence, more research is needed.

Author Contributions: Conceptualization, M.M.A.E.-A., N.Y., N.S.A., J.D., R.G. and S.A.H.; data curation, S.A.H., M.M.A.E.-A., E.Y., M.O., N.S.A. and N.Y.; formal analysis, M.H., A.H. and A.M.; funding acquisition, G.E.E.; investigation, M.M.A.E.-A. and S.A.H.; methodology, E.Y., M.H., M.O. and A.M.; resources, S.A.H. and G.E.E.; software, A.H.; supervision, M.M.A.E.-A. and S.A.H.; validation, M.M.A.E.-A., G.E.E., M.O. and J.L.; visualization, J.L. and S.A.H.; writing—original draft, M.M.A.E.-A., E.Y. and S.A.H.; writing—review and editing, M.M.A.E.-A., J.L., N.Y., N.S.A., J.D., R.G. and S.A.H. All authors have read and agreed to the published version of the manuscript.

Funding: This work was funded by the Researchers Supporting Project Number (RSP2023R161), King Saud University, Riyadh, Saudi Arabia. The publication was co-financed within the framework of the Polish Ministry of Science and Higher Education's program: "Regional Excellence Initiative" in the years 2019–2023 (No. 005/RID/2018/19)", financing amount 12,000,000,00 PLN.

Institutional Review Board Statement: Not applicable.

Data Availability Statement: Not applicable.

Acknowledgments: The authors would like to express their gratitude to the Agricultural Microbiology Department at Minia University for their support in this research.

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

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