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Applying Different Magnetic Water Densities as Irrigation for Aeroponically and Hydroponically Grown Strawberries

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Abstract: Due to the scarcity of water, it is necessary to develop an environmentally friendly method for increasing water productivity and crop production. An experiment was conducted to assess the effects of different magnetic levels (magnetic water level 1 (MWL 1) = 3800 Gauss, magnetic water level 2 (MWL 2) = 5250 Gauss, and magnetic water level 3 (MWL 3) = 6300 Gauss, as well as normal water (NW) as a control) in combination with three soilless culture systems (a nutrient film technique (NFT) hydroponics system, a tower aeroponics system, and a pyramidal aeroponics system. The results showed that the utilization of magnetic water had significant effects on the yield and growth of strawberry plants The tower aeroponic system under MWL 3 produced the highest yield and water productivity, with increases of 80.9% and 89%, respectively, over the control. The tower aeroponic system under MWL 3 produced the highest yield and water productivity, with increases of 80.9% and 89%, respectively, over the control. In addition, as compared to the NW, the NFT system increased yield and water productivity by 71.1% and 79.3%, respectively, whilst the pyramidal system increased yield and water productivity by 66.87% and 82%, respectively. Furthermore, when compared to the control, the combination of the NFT system and magnetic water level 3 (MWL 3) resulted in the most leaves, largest stem diameter, and largest leaf area of the strawberry plants resulted in the most leaves, stem diameter, and leaf area of strawberry plants. In comparison to all other treatments, this combination produced the best fruit quality and yield, as well as its constituents, such as titratable acidity, total soluble solids, and fruit hardness. This study found that combining magnetic therapy with soilless culture techniques resulted in increased yield and water productivity. In addition, water and fertigation solution usage in the NFT, tower, and pyramidal systems dropped by 4.8%, 6%, and 4.8%, respectively. Furthermore, it enhanced plant morphology and plant quality.

Keywords: aeroponics; strawberry yield and growth characteristics; magnetic water; water productivity; water consumption

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Citation: Mohamed, T.M.K.; Gao, J.; Abuarab, M.E.; Kassem, M.; Wasef, E.; El-Ssawy, W. Applying Different Magnetic Water Densities as Irrigation for Aeroponically and Hydroponically Grown Strawberries. *Agriculture* **2022**, *12*, 819. https://doi.org/10.3390/agriculture12060819

Academic Editor: Maria Giordano

Received: 26 April 2022
Accepted: 2 June 2022
Published: 7 June 2022

1. Introduction

The use of freshwater around the world has increased by more than double the population rate increase in the 20th century [1]. Water shortages have a significant impact on the agricultural sector. Currently, agriculture requires 70% of freshwater worldwide and accounts for more than 90% of its consumer use [2]. With rapid population growth and shifting dietary patterns worldwide, the demand for food is increasing across the globe [3]. Soilless cultures such as hydroponics and aeroponics can be the solution to the problems of producing intensive and safe food, controlling the environment, and determining appropriate levels of water and fertigation use. This is the technology of the future, to supply an adequate yield that meets the demands of consumers and their quality concerns [4]. Currently, soilless culture types are transformed from open systems to closed systems to improve water efficiency while maintaining yield quality [4]. Irrigation management of soilless culture systems is more sensitive than that of soil culture because its nutrition depends on the solution that reaches it, so any reduction in the delivery of the water solution may cause stress, leading to suboptimal plant growth or the deterioration of plant growth. The advantages of hydroponic and aeroponic systems over soil culture include more yield production per unit area compared to the ordinary or traditional soil cultivation, higher water use efficiency because of recycling, lower moisture stress, and greater oxygen concentration dissolved in the irrigation solution [5].

The design and method of irrigation management in hydroponics is the basis for increasing the efficiency of the hydroponic system. For example, when comparing the nutrient film technique (NFT) system with substrate systems, it is obvious that the water productivity is higher in NFT systems [6]. Furthermore, one of the main benefits of aeroponics and hydroponics as closed systems using the recycling of fertigation solution is the reduction of water loss and nutrients, thereby improving the efficiency of water use. In addition, the use of these systems leads to a decrease in environmental pollution problems. Water and fertigation are provided in traditional soil culture, which does not use the recycling of nutrients, leading to much water waste and pollution, such as the pollution of aquifers with fertilizers and pesticides [7].

NFT is a thin layer of solution sandwiched between two polyethylene sheets that forms a growth channel, resulting in an excellent connection between the recycled solution and air, allowing the roots to maintain their oxygen levels without the need for further solution ventilation [7]. Hydroponic agricultural production has increased considerably around the world recently, enabling the more efficient use of water and fertilizer to better control climatic and insect variables. Hydroponic production has also improved quality, productivity, competitiveness, and economic earnings [8]. In hydroponics, the fertilization solution is one of the most critical drivers of crop productivity and quality. Hydroponics consumes a fraction of the water that is utilized in soil cultivation.

Furthermore, aeroponics is regarded as a refined and improved approach for hydroponic growth methods. The main difference between aeroponics and hydroponics is that the nutrient solution is sprayed as a fine mist or fog in the root growing chamber, increasing the oxygen required by plants for greater absorption and growth. Furthermore, aeroponic systems do not require soil, only sponges or small net pots to sustain plants [9–12]. Furthermore, due to its nutrient solution recycling, this system is inexpensive in its usage of nutrients and water [11].

Different spraying nozzles (high air pressure and low air pressure) are used to supply nutrients in aeroponic systems [13]. When compared to traditional agricultural activities, aeroponics can eliminate external environmental influences because it uses an enclosed growth chamber with controlled ambient conditions [10].

Strawberry is also one of the most popular fruit crops in the world, and it is high in bioactive chemicals [14]. Strawberry production is concentrated in the north and middle regions of Europe, with the second largest concentration in the globe in the southwestern region of Spain (Huelva). Strawberry production in black plastic polyethylene beds necessitates large amounts of freshwater to meet crop water and other agricultural operations such as soil preparation and cultivation [15].

Water is made more available for plant absorption in aeroponic and hydroponic systems to reduce water irrigation use; as a result, more nutrient absorption reflects more strawberry productivity and more water productivity. This paper considers magnetic water treatment. According to Mohamed and Ebead [16], magnetic water is utilized to increase water production and save water supplies, especially as future water scarcity is expected. Seed processing with a magnetic field is currently being used to increase plant growth studies [17]. Much research has offered mechanisms for explaining how a static magnetic field interacts with biological systems [18,19]. The goal of this research was to see how different magnetic water densities affected the yield, quality, and features of strawberries cultivated aeroponically and hydroponically.

2. Materials and Methods

2.1. Experiment Location and Climate Conditions

The experiments took place in a controlled greenhouse at the Agricultural Engineering Research Institute, Agricultural Research Center, Giza, Egypt (lat. 30°11′ N, long. 31°41′ E, altitude 74 m above sea level) throughout two seasons in 2018 and 2019. During the growing season, the maximum air temperature was 24.5 °C, the minimum air temperature was 20.3 °C, and the average air relative humidity was 65%. Cooling pads, fans, and monitoring sensors (Model: CSP60BA252 M, with a nominal resistance of 2500 ohms and calibration throughout the range of 0 to 40 °C, made in China) were used to control temperature and humidity in the greenhouse.

2.2. Plant Material

Strawberry (*F.* × *Ananasa*) cv. a Festival transplants were placed in sponge-filled netting cups. Plants were placed in a greenhouse for three weeks in a deep water culture filled with a thin layer of diluted nutrient solution [18] until complete roots occurred (Table 1). After rooted, plants were moved to their final locations in various soilless systems. Nutrient solution was applied to an irrigation water tank, with a volume of 120 L, filled with the nutrient solution at (0.58 g L^{-1}), which is equal to 69.35 g for the whole tank.

Table 1. Element concentrations in the used fertigation solution [20].

Element Concentration (mg L^{-1})										
N	**P**	**K**	**Ca**	**Mg**	**Fe**	**Mn**	**Cu**	**Zn**	**B**	**Mo**
196.70	266.30	598.13	135	45	2.7	0.75	0.375	0.113	0.188	0.009

N is nitrogen concentration, P is phosphorus, K is potassium, Ca is calcium, Mg is magnesium, Fe is magnesium, ferric of iron, Mn is manganese, Cu is copper, Zn is zinc, B is boron, and Mo is molybdenum.

2.3. Systems Installation and Experimental Treatments

A randomized complete block design with 12 treatments was used in the study. During the plant growth period, all treatments had equal average temperatures, irrigation periods (15 min h^{-1}), and humidity. Three soilless culture systems were used in the experiment: a suspended NFT system, a pyramidal aeroponic system, and a tower aeroponic system, as well as four irrigation water treatments: normal water and magnetic water with three magnetic levels: magnetic water level 1 (MWL 1) = 3800 Gauss, magnetic water level 2 (MWL 2) = 5250 Gauss, and magnetic water level 3 (MWL 3) = 6300 Gauss. The systems were designed to hold an average of 64 plants per square meter in each system. An iron frame wrapped with a polyethylene sheet 2.0 m wide, 3.5 m long, and 2.5 m high was utilized to create an environmentally controlled greenhouse. The NFT system was a suspended shape system that was comprised of 1.5-m-high iron stands and 2.5-m-long pipes with a 4-inch diameter; the pipes were perforated with a 5-cm diameter hole. Plants were housed in the same gullies of plastic hydroponic cups put in holes with a 20-cm gap between them. This system included six pipes and 72 plants (Figure 1).

The pyramidal aeroponic system was made up of pyramidal iron frames that were 1.0 m wide by 1.0 m long. An iron bar was used to connect all of the frames. Plants were enclosed in high-density plastic sheets, with a 0.5 cm thickness, that were fastened on both sides of the frames, giving a pyramid shape. The shape was set on a 700-micron black polyethylene gutter with dimensions of 1 m width, 1 m length, and 0.30 m height, and it was used to collect excess nutrient solution and direct it to the fertigation tank. The system consisted of four plastic sheets containing a total of 100 plants. A one-horsepower pump delivered the fertigation solution to 16-mm polyethylene pipes connected to foggers positioned inside the system. The form was fitted with four foggers, each with a misting distance of 0.5, a flow rate of 6 L h^{-1}, and a spraying pressure of 2 bar (Figure 1).

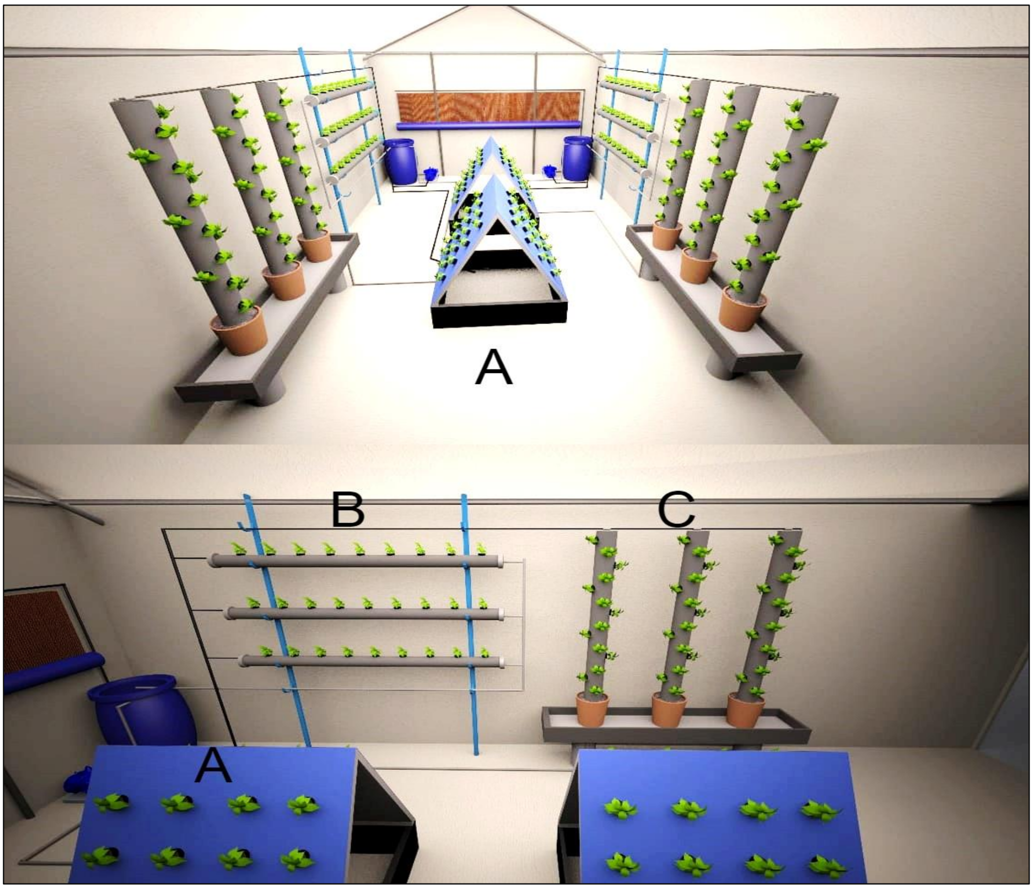


Figure 1. Layout of the environmentally controlled greenhouse and the different soilless culture systems of the experiment. (**A**) is the pyramidal aeroponic system, (**B**) is the nutrient film technique (NFT) hydroponic system, and (**C**) is the tower aeroponic system.

The tower aeroponic system stood 1.5 m tall and was made out of 6-inch diameter pipes. The plants were planted in plastic hydroponic cups at 20 cm intervals. This system had six pipelines and 84 plants in it. The system was irrigated with fertigation solution from a tank. A one-hp centrifugal pump pumped the nutrient solution through a 16-mm polyethylene tubing linked to the tower's upper end. A 16-mm polyethylene pipe carried the fertigation solution to foggers located inside the system. As seen in Figure 1, the fogger had the same properties as the previous fogger (Figure 1).

2.4. Magnetic Device (MD)

A pipe with a 3-inch diameter and a 20-cm length of permanent magnets made up the magnetic apparatus. These permanent magnets were built of neodymium magnets, which were made of a neodymium, iron, and boron alloy (NdFeB). The magnet's remarkable resistance to demagnetization is due to its tetragonal crystalline structure. Permanent magnets, which are used to construct magnetic devices, are pieces of magnetic material that keep their magnetic properties throughout time and stay magnetized in the absence of an external magnetic field (Figure 2). A Gaussian meter (Electronica flux meter DC 34, England) was used to measure magnetic density, and a Gaussian/tesla meter (F.W. BELL (5080, USA)) was used to measure general density with a basic accuracy of 1%.

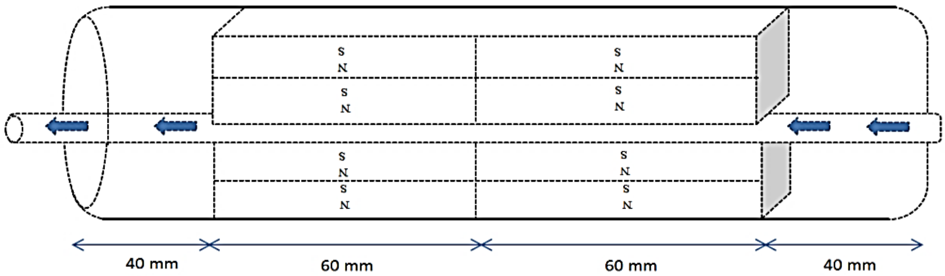


Figure 2. Sections of the magnetic device.

Magnets were grouped in four pairs in each unit, and magnets were classified into three types: the first type (piece A) had dimensions of 60 × 18 × 5 mm, the second type (piece B) had dimensions of 60 × 17 × 5 mm, and the third kind (piece C) had dimensions of 60 × 17 × 5 mm (Table 2). The magnetic units were established using the WIDDOWSON [21] equation, which states that increasing magnet length results in a stronger magnetizing force at the operational point.

$$A_m = \frac{B_g\, A_g}{B_m} \tag{1}$$

where B_m is the magnetic flux density at the operating point, A_m is the cross section of the magnet, A_g is the cross section of the void, and B_g is the magnetic flux density in the void.

Table 2. The different flux densities produced from the different magnetic unit pairings.

Magnetic Water Level	Magnets Paired	Flux Density (Gauss)
MWL 1	B + C//B + C	3800
MWL 2	A + B//A + B	5250
MWL 3	A + A//A + A	6300

Table 2 depicts the various magnet setups utilized to produce the applied flux densities employed in the studies. Equation (2) computes the water flow velocity through the magnetic unit to be 3.15×10^{-3} m s^{-1} [22]. Magnetic field memory in the water was tested using a pH meter (Ecosense pH100, 0.1%, Metrohm, Herisau, Switzerland), which also served as a magnetic field memory meter. This characteristic (water memory) must be specified and may be described as the time at which the magnetized water remembers the influence of the magnetic field. The pH value can be thought of as a water memory meter [23].

$$Q = A \times V \tag{2}$$

where Q is the water flow rate (m^3 s^{-1}), A is the cross-sectional area (m^2), and V is the velocity of water (m s^{-1}).

2.5. Evaluation of Irrigation Systems

The application uniformity was determined to examine how equal the water distribution was for various outputs, operating pressures, and nozzle heights. The Christiansen uniformity coefficient (CU) and distribution uniformity (DU) were used to calculate application uniformity [24,25]. The uniformity coefficient developed by CHRISTIANSEN [26] is as follows:

$$CU = 100\left(1.0 - \frac{\sum_{i=1}^{n}|z - m|}{\sum_{i=1}^{n} z}\right) \tag{3}$$

where CU is the Christiansen uniformity coefficient, z is the individual depth of catch observations from the uniformity test (mm), m is the mean depth of observations (mm), and n is the number of observations [27]. The distribution uniformity is a ratio expressed in a percent of the average low-quarter amount caught or infiltrated to the average amount caught or infiltrated as expressed in the following equation [28]:

$$DU = 100\frac{\bar{X}_{LO}}{\bar{X}}. \quad (4)$$

Where $\bar{X}_{LO}$ is the average low-quarter amount caught or infiltrated (mm), and $\bar{X}$ is the average amount caught or infiltrated (mm).

A square pattern was used with a 4-cm diameter of cans and a 10-cm space between cans, under the assumption that there would be no wind. This method of determining CU has the advantage of controlling all factors in the process, especially sprinkler water distribution. Thus, we established comparisons between the application uniformity at different operating pressures and different foggers as replicates to avoid errors [29] (Table 3).

Table 3. The hydraulic evaluation parameters of foggers at different operating pressures. Mean values are given (percentage).

Evaluation Parameter	Operating Pressure (Bar)				
	1.5	**1.75**	**2**	**2.25**	**2.5**
CU (%)	90.20	91.92	96.96	91.96	93.90
DU (%)	82.26	88.90	96.70	87.74	92.00

CU is Christiansen uniformity coefficient, and DU is distribution uniformity.

2.6. Assessment Criteria

Flow rate was measured by an Arduino flow meter, which are designed and manufactured specially for hydroponic systems because they do not need high pressure to calculate water flow through pipes. The water flow sensor consists of a plastic valve body, a water rotor, and a hall-effect sensor. When the water flows through the rotor, the rotor rolls, and the speed of it changes with a different rate of flow. The hall-effect sensor outputs the corresponding pulse signal. The flow meter was evaluated before use, by the evaluation of water volume via the scaling tester.

The circuit of the flow meter depends on two sections; the first section is analog, which uses signals or information represented by a continuously variable physical quantity to program the Arduino microcontroller. The second section is digital, which receives the signal from the flow rate sensor and transfers it to the microcontroller to store it in the memory card.

The Arduino flow meter consisted of a flow rate sensor (valve body) ((model: FS300AG3/4″) flow range: 1–30 L min^{-1}, working pressure < 1.2 Mpa (Sea) YF-21, made in Italy), Arduino microcontroller (model: tutorial—Uno R3, made in Italy), pull up resistor (Resistor 10K ohm), wires (to transfer the signals from sensor to microcontroller and store them in the memory card), memory card (32 Giga), and battery (battery type: Zinc Carbon, made in China (9 V)).

Every week, along with the culture period, the pH and total dissolved solids (TDS) of the fertigation solutions were assessed for each treatment group by a digital pH meter (ATC, China, with 0.1 pH resolution and 0.1 pH accuracy) and a 3in1 TDS device (Water World Company, Missouri City, TX, USA), used to measure TDS with a 2% accuracy. Three plants were randomly selected from each condition after five months of transplanting to measure nutrient absorption (N.P.K.). A Kjeldahel digestion technique was used to determine the total nitrogen (N) content.

The total phosphorous (P) concentration was calculated using automated colorimetry (molybdovanadate technique), and the total potassium (K) content was assessed using a flame photometric method [12]. Furthermore, during the harvest stage, three plants were randomly selected from each treatment to assess plant growth metrics such as the number of leaves per plant, stem diameter, leaf area, plant height, fruit number, fruit volume, and fresh weight of fruits. The diameter of the stem and the height of the plant were measured using an electronic digital caliper with an accuracy of 0.02 mm. Three plants were chosen at random from each treatment to estimate the total leaf area per plant using digital image processing with ImageJ software, as reported by O'Neal, Landis [30].

An HP Scanjet G4010 desktop scanner was used to scan and save individual leaves in digital format. The amount of water displaced in the tester when the fruit was put in was used to calculate the volume of fruit. A computerized balance was used to determine the weight of the fruits (Chyo balance corp., Japan, accuracy of 0.01 g). Each system's total fruit weight was gathered and weighed, and the results were given as (g plant^{-1}) and (kg m^{-2}). Titratable acidity was calculated by titrating fruit sap samples with NaOH (0.1 N) until the pH reached 8.2. Equation (5) was then used to obtain the citric acid content:

$$\text{Acidity } (\%) = \frac{0.064 \times \text{Used NaOH} \times \text{NaOH factor}}{\text{Sample weight}} \times 10 \tag{5}$$

The soluble solids content (SSC) of the fruit juice was measured by using a refractometer (BOEO32195, accuracy 0.05, Germany). Firmness was measured by a penetrometer (PENETROMETRO ST 308, made in Italy; accuracy $\pm$ 0.1%). An EC meter was used to test the electrical conductivity of the irrigation water (Ecosence EC300, accuracy 0.2%, Germany). A pH meter was used to determine the pH of the irrigation water (Ecosense pH 100, 0.1%, Germany).

The crop water use for each system (plant water consumption) was estimated using the Equation (6) below [31]:

$$\text{CWU} = \frac{Q_1 - Q_2}{A} \times 10.00 \tag{6}$$

where CWU is the crop water use (m^3 ha^{-1}), Q_1 is the inflow volume to every system (m^3 system^{-1} m^{-2}), Q_2 is the drainage outflow volume from the greenhouse (m^3 system^{-1} m^{-2}), and A is the area of the system (m^2). The difference between the inflow and outflow nutrient volumes could be found out by measuring the decrease of the nutrient solution levels in the tanks below the definite level at the beginning of the experiments [32]. The water productivity (kg m^{-3}) was computed using Equation (7) [33].

$$\text{Water productivity } \left(\text{kg m}^{-3}\right) = \frac{\text{yield } \left(\text{kg ha}^{-1}\right)}{\text{Crop water use } \left(\text{m}^3 \text{ ha}^{-1}\right)} \tag{7}$$

2.7. Statistical Analysis

The acquired data were statistically analyzed using ANOVA in SAS [34]. In the same software, mean separation was performed using LSD (p = 0.05), which is useful for randomized full block design in factorial arrangement with two factors: soilless culture systems, irrigation water treatments, and replicates as blocks. As an error term, the mean square of the values generated by the interaction between the soilless culture systems and irrigation water treatments was employed. In the ANOVA, the statistically significant differences between the average groups were defined using Duncan's least significant difference (LSD). In addition, all the obtained data were conducted in triplicate, and the results were reported as average values $\pm$ standard deviation (SD) from three replicates.

3. Results and Discussion

3.1. Irrigation Nutrient (Fertigation) Solution Properties

The two seasons showed the same data, and to not repeat the data, we demonstrate the last season of this experiment (2019) in Table 4. The magnetic water levels had significant effects on the nutrient solution of the irrigation water. Although, the MWLs had no significant effect on pH where the pH was fixed from the control to MWL 1. The MWLs had significant effects on total dissolved solids (TDS), where TDS was increased by increasing the magnetic flux density, and the highest TDS was achieved by MWL 3, with an increment percentage of 3.3%. Magnetic flux density had an effect on nitrogen (N), with the greatest N in the control, decreasing as the magnetic flux density increased. There was also no significant difference between the control and MWL 1; however, a significant difference existed between the control and MWL 2 and MWL 3. When compared to the control, the percentages that decreased as a result of employing MWL 3 and MWL 2 were 9.46% and 9.45%, respectively. The amount of phosphorus (P) was not altered by magnetic flux density, and the statistical analysis indicated that there was no significant difference between all of the treatments. However, increasing magnetic flux density raised P marginally, and MWL 3 had the greatest P. Furthermore, when the magnetic flux density was reduced (MWL 1 and MWL 2), phosphorus levels were reduced. Potassium (K) was considerably impacted by magnetic flux density, and it was raised by increasing magnetic flux density, with MWL 3 achieving the greatest K and the control treatment achieving the lowest K, although there was no significant difference between them. These slight changes in NPK values may have resulted from the effect of the magnetic force on the water clusters and the angle between the hydrogen and oxygen of water atoms. In addition, the decrease in N concentration of nutrient solution may be due to the increase of the nutrient absorption by the plants.

Table 4. Effects of different magnetic levels on pH, TDS, N, P, and K concentrations in the nutrient or fertigation solution; mean values and standard errors (SE) are given.

Nutrient Solution	pH	TDS (ppm)	N (mg L^{-1})	P (mg L^{-1})	K (mg L^{-1})
Control	6.4 ± 0.00^{ns}	1263 ± 0.40^{d}	196.70 ± 0.57^{a}	266.30 ± 1.15^{ns}	598.13 ± 2.31^{ns}
MWL 1	6.3 ± 0.02^{ns}	1271 ± 0.89^{c}	196.70 ± 1.73^{a}	259.80 ± 2.88^{ns}	598.00 ± 1.73^{ns}
MWL 2	6.2 ± 0.02^{ns}	1282 ± 1.65^{b}	178.10 ± 1.73^{b}	251.29 ± 0.58^{ns}	603.00 ± 0.06^{ns}
MWL 3	6.2 ± 0.02^{ns}	1305 ± 3.51^{a}	178.08 ± 0.01^{b}	272.04 ± 1.15^{ns}	603.20 ± 1.15^{ns}
$LSD_{(0.05)}$	-	1.9	4.10	-	-

Each value represents the mean ± SE. Small superscripted letters represent the significance level while comparing values in the same column. Superscripted ns mean that there is no significant difference between treatments in the same column. LSD is least significant difference at $p \leq 0.05$, TDS is total dissolved solids with (ppm), which is a part per million. MWL 1 is magnetic water level 1, MWL 2 is magnetic water level 2, and MWL 3 is magnetic water level 3. N is nitrogen concentration, P is potassium level, and K is potassium level.

The results of TDS and P are consistent with Maheshwari and Grewal (2009), where TDS increased by 0.4% and P increased by 2.27% as a result of using magnetic water treatment. However, the results of pH, N, and K are inconsistent, where they reported that N increased by 1.18% as a result of using magnetic treatment, pH increased by 0.24%. However, K decreased by 4.1% with the use of magnetic treatment for water.

The effect of magnetized water within the fertigation tanks on mosquito spread, on the other hand, was noticed with the naked eye (results not listed). The use of a magnetic field in soilless culture irrigation systems prevents the growth of mosquito larvae, which develop rapidly in standard water tanks and can harm public health. Mosquitos entered the greenhouse as a result of the frequent opening and closing of the greenhouse entrance for plant observation and data collecting. This finding is consistent with the findings of Ibrahim and Baz [19], who discovered that a magnetic field altered the quantity of mosquitos that reached the adult stage, which then entered the environment and caused progeny weakness and disease prevalence, and magnetic intensity significantly affected the mortality of larvae, where it increased with increasing magnetic intensities.

3.2. Irrigation Water Consumptions

After 10 days of transplanting and throughout the strawberry seasons, the water administered for several soilless culture methods under normal water (NW) and magnetic water levels (MWLs) was determined. The two seasons used the same data, and to avoid repeating the experiment, we display the last season (2019) in Figure 3. The results showed that the NFT system consumed more water than the tower aeroponic system and pyramidal aeroponic system for the control treatment (NW), with a significant ($p \leq 0.05$) difference between NFT and pyramidal aeroponic system, but no significant difference between NFT and tower aeroponic system, though the tower system consumed less water. The maximum daily water usage that happened in the NFT system at the stage between 90 days and 100 days was 1.48 L plant^{-1}, while in the tower and pyramidal system the maximum usage was 0.88, and 0.92 L plant^{-1} at the stages between the days 100–110 and 110–120, respectively, as shown in Figure 3A. The statistical analysis of the MWL 1 treatment revealed no significant ($p > 0.05$) difference between the three systems (NFT, tower, and pyramidal systems), as shown in Figure 3B. The data analysis indicated a significant ($p \leq 0.05$) difference between the NFT and both the tower and pyramidal aeroponic systems in the case of MWL 2 treatment. The highest daily water consumption in the NFT, tower, and pyramidal systems throughout the 100–110-day stage was 1.5, 0.89, and 0.85 L plant^{-1}, respectively, as shown in Figure 3C. Furthermore, the results of the MWL 3 therapy were the same as those of the MWL 2 treatment. NFT had the highest daily water use, and the NFT, tower, and pyramidal system water use at the stage between the 100–110 days were 1.4, 0.86, and 0.85 L plant^{-1}, respectively, as shown in Figure 3D.

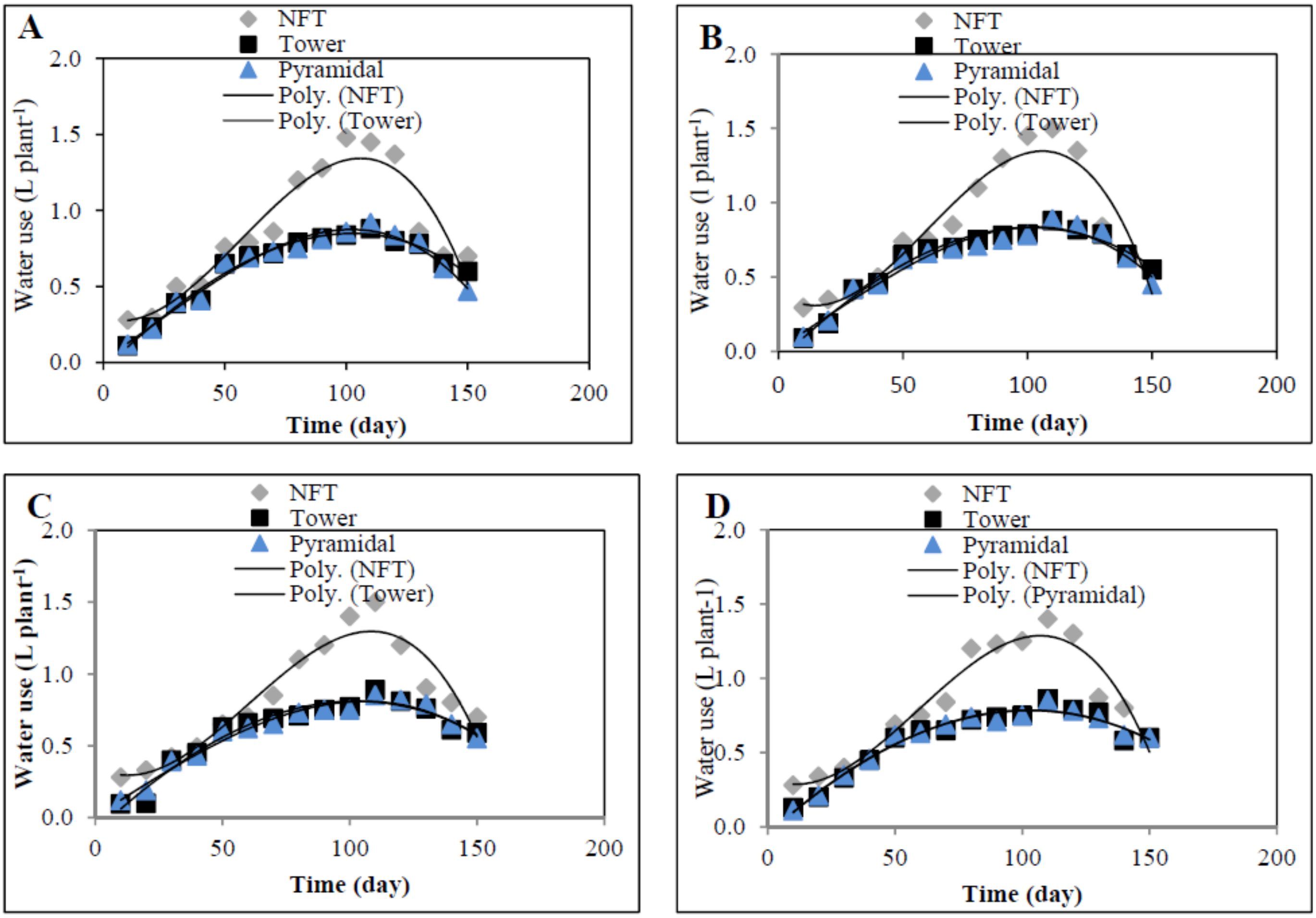


Figure 3. The daily water consumption of different stages (each stage 10 days) for different soilless culture systems under normal and magnetic water along with cultivation period. (**A**) is water use in the case of the control (without using any magnetic treatment). (**B**) is water use in the case of MWL 1. (**C**) is water use in the case of MWL 2. (**D**) is water use in the case of MWL 3.

In addition, Figure 4 demonstrated the total water consumption (L plant^{-1}) for each treatment (NW, MWL 1, MWL 2, MWL 3). Under the three soilless culture systems, there was a significant ($p < 0.05$) difference between total water applied under NFT and both the tower and the pyramidal aeroponics systems. The maximum water consumption was registered in the NFT system irrigated by normal water (NW) 13.035 L plant^{-1}, and the minimum total water consumption was 12.41 L plant^{-1} at MWL 3, with a reduction percentage in total water consumption by the plant (4.8%) as a result of applying MWL 3. In addition, we found that the total water consumption by plant in the case of the tower system was higher in NW than MWL 3, which were 9.37 and 8.82 L plant^{-1}, respectively. The reduction in total water use by plant as a result of using MWL 3 was approximately (6%). Furthermore, in the case of the pyramidal aeroponics system, the total water used by crop at NW and MWL 3 was 9.29 and 8.84 L plant^{-1}, and the percentage of reduction was (4.8%) as a result of using MWL 3. The minimum water consumption was realized in the tower aeroponic system with magnetic water level 3 (MWL 3), as shown in Figure 4. All these results agreed with El-Ssawy, et al. [35]; they showed that increasing magnetic strength reduced water use in all hydroponic systems compared to the control. Tower and pyramidal systems, on the other hand, used less water than the NFT system.

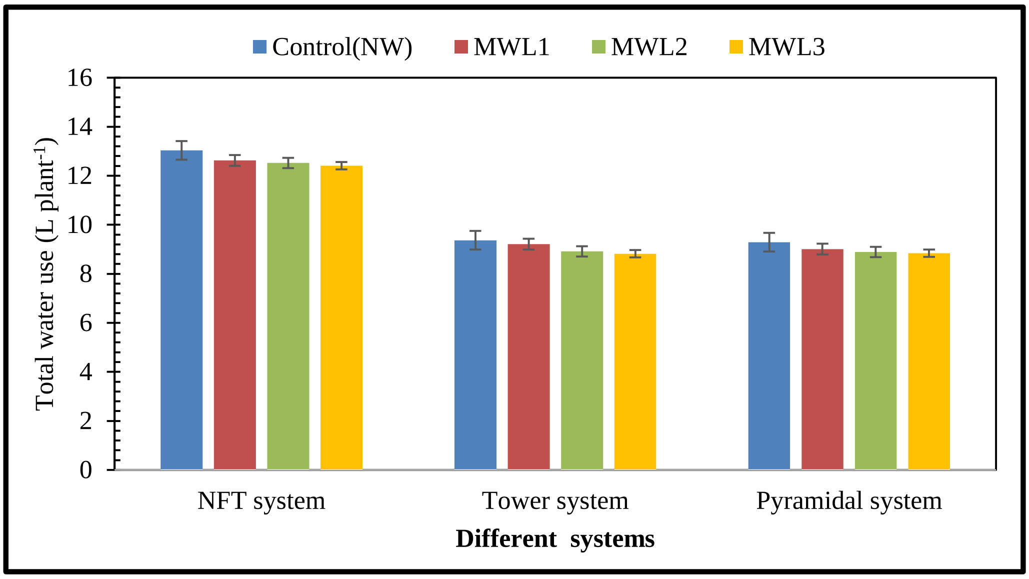


Figure 4. Total crop water used for different soilless culture systems under normal and magnetic water. LSD $_{(0.05)}$ = 8.82.

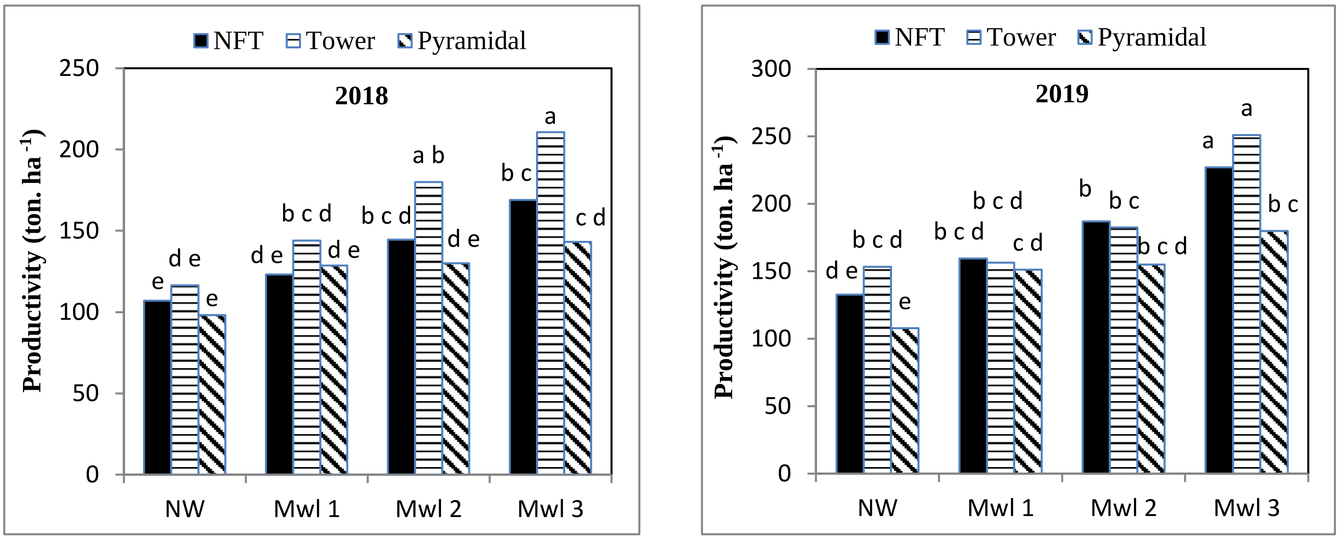
The indirect impact of magnetic treatment on water, where the surface tension mechanism plays a role in water uptake by plant roots, can explain the reduction in water consumption. Water surface tensions provide a high gradient in hydrostatic pressure that favors the apoplastic component of water absorption, in which the transport process in the plant composite, as well as the cohesion and tension mechanism of sap ascent, play essential roles [36]. Furthermore, the magnetic strength affects the water surface tension; a magnetic field of 2000–3000 Gauss resulted in the lowest surface tension coefficient, the best magnetization effect, and the greatest surface tension reduction [37]. Furthermore, some studies revealed that there are many impacts of magnetic densities on physical characteristics of water, such as Alwediyani, et al. [38], who mentioned that the density and surface tension decreased by 4.4% and 4.62%, respectively. In addition, Wang, et al. [39] reported that there was a decrease in specific heat and boiling point after the magnetization of water.

The findings in Figure 4 contradict those of Maheshwari and Grewal [40], who reported that the magnetic treatment of water had no influence on the total water utilized by plants throughout the growth period for any of the irrigation water types (magnetic and normal water). The experiment was carried out on soil cultivation, using a magnetic field with a range of 35–1360 Gauss.

3.3. Yield and Water Productivity

The yields produced using different soilless cultivation techniques and different irrigation water treatments differed significantly. In the first and second seasons, the largest yield was recorded by the tower aeroponic system under MWL 3 (210.65 and 251.11 ton ha^{-1}, respectively); whereas in the second season, there was no significant difference between the tower aeroponic system under MWL 3 and the NFT system under the same MWLs. In the first and second seasons, the increase percentage in the tower aeroponic system treated with MWL 3 was 80.9% and 63.7%, respectively, as compared to the control. In the first and second seasons, the percentage of increase in the NFT system under MWL 3 was 57.8% and 71.1%, respectively, compared to the NW.

Furthermore, in the first and second seasons, MWL 3 treatment on the pyramidal aeroponic system resulted in increment percentages of 45.9% and 66.87 percent, respectively, when compared to the control. In the first and second seasons, the minimum yield was observed under a pyramidal aeroponic system under NW (98.12 ton ha^{-1}) and (107.82 ton ha^{-1}). In the first and second seasons, the yield increment percentage between the greatest and lowest reported yield values was 114.69% and 132.90%, respectively (Figure 5). According to Antunes, et al. [41], the highest production of strawberry (*F.* × *Ananasa*) in soil for cultivar festivals was 37.36 ton ha^{-1}.



LSD 0.05 = 36.064 LSD 0.05 = 34.374

Figure 5. Strawberry productivity of different soilless culture systems under normal and magnetic water. Lowercase letters a–e are homogeneous groups; means followed by the same letters are not significantly different from one another based on Duncan's protected LSD test ($p \leq 0.05$).

According to Antunes, et al. [41], the highest production of strawberry (*F.* × *Ananasa*) in soil for cultivar festivals was 37.36 ton ha^{-1}. The improvement in yield in this study, as a consequence of utilizing MWL 3, might be attributed to an increase in plant nitrogen absorption, as indicated in Table 4, where there was a decrease in N concentration in the fertigation tank treated with MWL 3 as a result of higher plant absorption. According to Leghari et al. (2016), N is the most important element for proper plant growth and development, as it considerably raises and improves plant output and quality by partaking in biochemical and physiological activities inside the plant.

The greatest water productivity was recorded in the first season under a tower aeroponic system irrigated with MWL 3 (37.81 kg m^{-3}), with an increase percentage of 89% when compared to the control under the tower aeroponic system. The greatest water production in the second season was achieved by applying the MWL 3 treatment to the tower system (44.48 kg m^{-3}), with a 71% increase over NW under the tower aeroponics system. In the case of the NFT system, the highest and minimum water productivity values were 22.5 kg m^{-3} and 12.8 kg m^{-3} under MWL 3 and NW, respectively, with a 75% increment percentage in the first season and 79.3% in the second season. Furthermore, the water productivity in the pyramidal aeroponic system increased by 58.1% in the first season to 16.5 kg m^{-3} under NW and 26.1 kg m^{-3} under MWL 3. While in the second season, the increment was 82% as a result of utilizing MWL 3 compared to NW. In addition, the increment percentage between the maximum water productivity in the tower aeroponics system (37.81 kg m^{-3}) and minimum value in the NFT system (12.8 kg m^{-3}) was 195.4%, while in the second season, the increment percentage between the maximum and minimum water productivity was 178% (Figure 6).

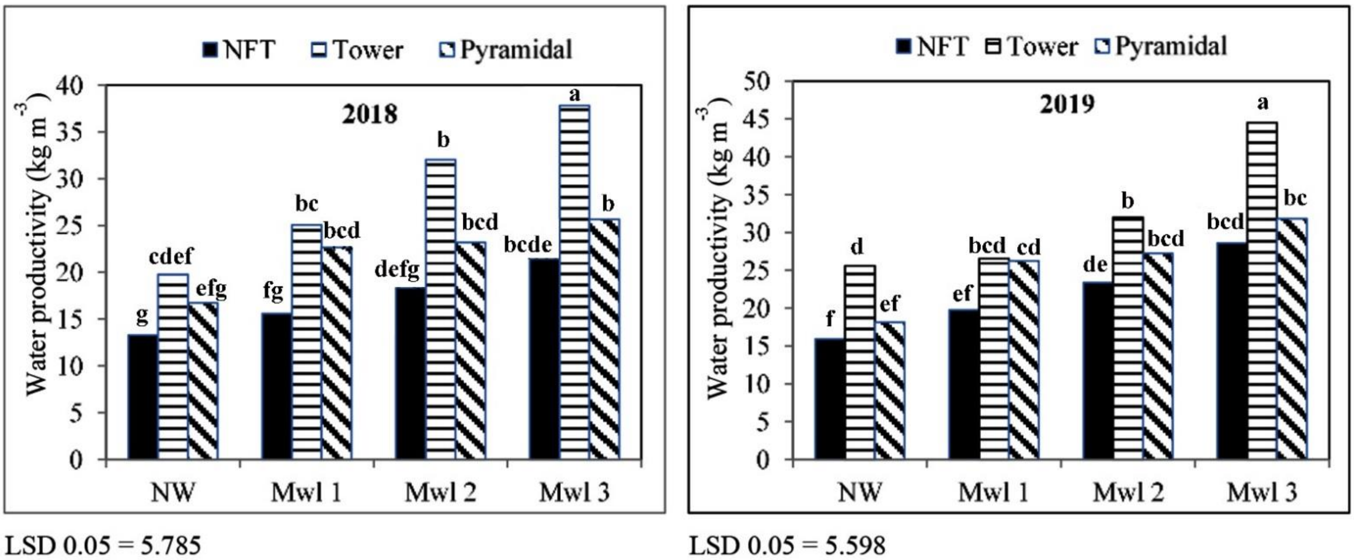


Figure 6. Water productivity of soilless culture systems under normal and magnetic water levels. Lowercase letters a–e are homogeneous groups; means followed by the same letters are not significantly different from one another based on Duncan's protected LSD test ($p \leq 0.05$).

This increment in water productivity may be due to the decrease of water consumption of the plant; it also may be due to an increase of the plant nutrient absorption, especially N, which leads to an improvement of the plant metabolism and other functions. Morillo, et al. [15] reported that the average results for water productivity were (8.85–9.80 kg m $^{-3}$) cultivation in the soil, which means there is more demand for water in the soil for producing strawberry. In the same context, Grewal, et al. [31] showed that the recycling of drainage water saved 33% of water consumption in the NFT system for cucumber production. Maheshwari and Grewal [40] proved that water productivity increased by 4.38% and 12.12% when using a magnetic field to treat normal water. Soilless culture can be an effective tool to increase crop yield, and the adoption of closed irrigation systems could increase water use efficiency. In addition, soilless culture systems reduce the environmental impact of greenhouses and nurseries. Our results were consistent with those of O. Sadeghipour [42], who revealed that magnetized water had a positive effect on production and water use efficiency, where the enhancement was 24% and 22% for production and water productivity, respectively. In agreement with our results, Al-Khazan, et al. [43] showed that magnetic water caused an increase in the water productivity of Jojoba.

3.4. Plant Growth Parameters

The largest number of leaves was recorded using the tower aeroponic system and MWL 3 (number of leaves = 36), with a 44% increase over the control, while the least number of leaves was recorded using the NFT system and MWL 1 (number of leaves = 15). Furthermore, in the second season, the largest number of leaves was recorded using the tower aeroponic system and MWL 3 (number of leaves = 36), with a 56.5% increase above the control (Table S1). The number of leaves was lower than that reported by Murthy, et al. [44], who found that strawberries had a greater leaf number when grown in soilless culture on a vertical system. However, our findings were better than those of Youssef and Abou kamer [45], who found that using a magnetic field to treat the nutritional solution increased the number of plant leaves by just 27%.

The tower aeroponic system and MWL 3 were used to measure the maximum stem diameter (1.35 and 1.33 cm in the first and second seasons, respectively). The difference in stem diameter between the tower system under MWL 3 and the NW of the same system (1.01 cm) in the first season was 33.66% (Table S1). The increase in stem diameter between the tower system under MWL 3 and the NW of the same system was 44.5% in the second season. The stem diameters, on the other hand, were less than those found by Claire, et al. [46], who measured 1.705 cm.

For the first season, the maximum plant height value was achieved under the tower aeroponic system with MWL 2 (20.83 cm), and there was no significant difference between it and the pyramidal and tower aeroponic systems under MWL 3. For the second season, the maximum plant height value was achieved by the NFT system with MWL 3 (20.33 cm) (Table S1). These results mean that the magnetic water treatment had an effect on plant height, but the hydroponic system did not affect the plant height of strawberries. In addition, the maximum number of fruits per plant was registered by the interaction between the NFT system under MWL 3 for the first season (15.33) and the NFT system under MWL 2 (16.33) for the second season (Table S1). The increment in strawberry fruit number was 21% and 19.5% for the first and second seasons, respectively.

These percentages were lower than the percentages obtained by Houda, et al. [47], who reported that the increment in strawberry fruit number was 43.5% and 27.4% in two different seasons when irrigated with magnetic water under soil culture. In the same context, El-Sayed, et al. [48] reported that the average number of fruits using mineral solution was 19.41 under several mixed media of peat moss, perlite, vermicompost, and plant compost. The interaction between systems and MWLs in the first season had no significant effect on leaf area, but the tower aeroponic system and MWL 3 had a higher leaf area (23.74 cm^2), while the minimum leaf area was achieved under pyramidal aeroponic and MWL 3 conditions (17.47 cm^2). However, there was a considerable difference in the values of leaf area in the second season, with the NFT system achieving the maximum value under MWL 3 (Table S1). Furthermore, the combination between the tower aeroponic system and MWL 3 yielded the highest fruit quantities (20.17 and 25.37 cm^3 for the first and second seasons, respectively). The combination of the pyramidal aeroponic system with NW yielded the lowest fruit volume (10.40 and 11.13 cm^3 for the first and second seasons, respectively) (Table S1).

The significant difference between treatments in the tower system may be related to the moisture being higher than that of the pyramidal system; thus, there was a lower water stress on fruits. This data are similar to the results obtained by Treftz and Omaye [49], where the water stress was necessary for hydroponic strawberry yield production to increase fruit size, since the plants were in their optimum growing conditions all the time.

The interaction between the tower aeroponic system and MWL 3 produced the maximum fruit weight (21.92 and 27.06 g for the first and second seasons, respectively), whereas the interaction between the pyramidal aeroponic system and NW produced the lowest fruit weight (11.79 and 12.32 g for the first and second seasons, respectively). As a result, the increases were 85.92% and 119.64%, respectively, when compared to the greatest and lowest fruit weight values for the first and second seasons (Table S1). El-Ssawy, et al. [35] observed that growing plant weight is dependent on increasing MWL. Furthermore, the collected results corresponded with the data obtained by Sandra VOĆA [50], who reported that the weight of fruit in soilless culture was 21 g compared with that in a high tunnel (20.0 g) and field (17.0 g). Alternatively, Antunes, et al. [41] reported that the average mass of fruit for cv. festival under soilless culture was 16.84 g when comparing strawberry fruit mass in several cultivars. Miranda, et al. [51] found that the maximum mean fruit weight was produced by the gutter system (similar to the NFT system) for several cultivars (10.17 g).

Total fruit weights per plant were highest when the tower aeroponic system was combined with MWL 3 (329.14 and 392.37 g for the first and second seasons, respectively), while the lowest total fruit weight per plant was obtained when the pyramidal aeroponic system was combined with NW (153.33 and 168.47 g for the first and the second seasons, respectively). When comparing the tower aeroponic system under MWL 3 to the identical system under normal water, the increment percentage was 80.97% (Table S1).

These values do not agree with Eşitken and Turan [52], who reported that a low intensity magnetic field had positive effects on strawberry fruit yield. Correia, et al. [53] showed that the maximum fruit weight per strawberry plant was 172 g and 132 g for 'Ventana and Candonga' strawberry in hydroponic systems. Murthy, et al. [44] reported that the maximum total fruit weight per plant was 195 g when they compared tiers of vertical soilless culture. Our study values were higher than the total fruit weight per plant reported by Talukder, et al. [54], where it was 225 g. The improvement of plant morphology achieved by using the magnetic water treatments, especially MWL 3, may be due to the enhancement of the fertigation solution absorption by the plant and the availability of the elements in the solution, which led to the improvement of the biochemical functions of the plant [55].

3.5. Quality parameters

The interactions of different soilless culture techniques and irrigation water treatments had a substantial effect on titratable acidity (TA), total soluble solids, and fruit firmness. The contact between the pyramidal aeroponic system and normal water produced the highest TA value (1.01% and 1.12% for the first and second seasons, respectively), whereas the interaction between the tower aeroponic system and MWL 3 produced the lowest TA value (0.89% and 0.74% for the first and the second seasons, respectively). For the first and second seasons, the TA increment percentages were 13.45% and 51.35%, respectively (Table 5). When compared to soil culture, Cecatto et al. (2013) found that greater values of TA for substrate (0.74%) were obtained (0.69%). When evaluating strawberry yield in various cultivars, Antunes et al. (2010) showed similar TA data for festival cultivars (0.74%).

The interaction between the tower aeroponic system and MWL 2 was the most effective on the soluble solids content (SSC) value (9.00° Brix) for the first season, while the interaction between the tower aeroponic system and MWL 3 was the most effective on the SSC value (10.20° Brix) for the second season. The lowest SSC value was obtained under the interaction between pyramidal aeroponics and NW (7.40 and 7.23° Brix for both the first and second seasons) (Table 5).

The explanation of these results may be found in the outcomes achieved by Palencia, et al. [56], who reported lower SSC values of strawberry, according to greater fruit yields in different substrates, where the higher value of SSC was 7.59° Brix in the agro-textile substrate. Cecatto, et al. [57] reported that a larger SSC value of strawberry was registered under the substrate (6.81° Brix) compared with soil culture. The highest firmness value was recorded under the interaction between the pyramidal aeroponic system and MWL 3 (0.78 kg cm^{-2}) for the first season, and the highest firmness value was recorded under the interaction between the NFT system and NW (0.89 kg cm^{-2}) for the second season. The lowest firmness value for the first season was achieved under the combination of the NFT system with NW (0.67 kg cm^{-2}), and for the second season was the combination of the tower aeroponic system with MWL 3 (0.64 kg cm^{-2}) (Table 5).

These results are greater than those produced by Sandra VOĆA [50], who reported that the value for fruit firmness in soilless culture was 0.64 kg cm^{-2} compared to the firmness values of fruits grown under soil culture and high tunnel conditions, where the firmness values were 0.76 kg cm^{-2} and 0.74 kg cm^{-2}, respectively.

Table 5. The influence of soilless culture systems, irrigation water magnetic treatments and their interaction on titratable acidity (TA), soluble solids content (SSC), and firmness of strawberry fruits. Mean values are given.

Irrigationwater Treatment (I)	2018				2019			
	Soilless Culture (S)							
	NFT	Tower Aeroponic	Pyramidal Aeroponic	NFT	Tower Aeroponic	Tower Aeroponic	NFT	Tower Aeroponic
	Titratable acidity (%)							
NW	0.95 ^{bc}	0.96 ^{b}	1.01 ^{a}	0.97 ^{a}	0.94 ^{b}	0.94 ^{b}	1.12 ^{a}	1.00 ^{a}
MWL 1	0.93 ^{bcd}	0.90 ^{bcd}	0.93 ^{bcd}	0.92 ^{b}	0.92 ^{b}	0.93 ^{b}	0.95 ^{b}	0.93 ^{b}
MWL 2	0.94 ^{bcd}	0.90 ^{cd}	0.95 ^{bcd}	0.93 ^{b}	0.88 ^{b}	0.87 ^{b}	0.93 ^{b}	0.89 ^{b}
MWL 3	0.93 ^{bcd}	0.89 ^{d}	0.95 ^{bc}	0.93 ^{b}	0.77 ^{c}	0.74 ^{c}	0.77 ^{c}	0.76 ^{c}
Mean	0.94 ^{a}	0.91 ^{b}	0.96 ^{a}		0.88 ^{b}	0.87 ^{b}	0.94 ^{a}	
LSD $_{(0.05)}$	S = 0.0243	I = 0.0281	S × I = 0.4861		S = 0.04	I = 0.05	S × I = 0.09	
	Soluble solids content (Brix °)							
NW	7.67 ^{def}	8.53 ^{b}	7.40 ^{f}	7.867 ^{c}	8.13 ^{de}	8.87 ^{bcde}	7.23 ^{f}	8.08 ^{c}
MWL 1	7.87 ^{cde}	8.83 ^{a}	7.63 ^{ef}	8.11 ^{b}	8.50 ^{bcde}	8.97 ^{bcde}	8.07 ^{e}	8.51 ^{bc}
MWL 2	7.97 ^{cd}	9.00 ^{a}	7.83 ^{cde}	8.27 ^{ab}	8.70 ^{bcde}	9.30 ^{b}	8.37 ^{cde}	8.79 ^{b}
MWL 3	8.13 ^{c}	8.97 ^{a}	7.97 ^{cd}	8.36 ^{a}	9.17 ^{bc}	10.20 ^{a}	8.87 ^{bcde}	9.41 ^{a}
Mean	7.91 ^{b}	8.83 ^{a}	7.71 ^{c}		8.63 ^{b}	9.33 ^{a}	8.13 ^{c}	
LSD $_{(0.05)}$	S = 0.1597	I = 0.1383	S × I = 0.2766		S = 0.39	I = 0.45	S × I = 0.78	
	Firmness (kg cm^{-2})							
NW	0.67 ^{d}	0.70 ^{bcd}	0.72 ^{bc}	0.69 ^{c}	0.89 ^{a}	0.81 ^{bc}	0.87 ^{ab}	0.86 ^{a}
MWL 1	0.68 ^{d}	0.73 ^{b}	0.78 ^{a}	0.73 ^{b}	0.86 ^{ab}	0.78 ^{c}	0.86 ^{ab}	0.83 ^{a}
MWL 2	0.68 ^{cd}	0.71 ^{bc}	0.77 ^{a}	0.72 ^{b}	0.76 ^{c}	0.76 ^{c}	0.85 ^{ab}	0.80 ^{b}
MWL 3	0.69 ^{bcd}	0.76 ^{a}	0.78 ^{a}	0.75 ^{a}	0.68 ^{d}	0.64 ^{d}	0.79 ^{c}	0.70 ^{c}
Mean	0.68 ^{c}	0.73 ^{b}	0.76 ^{a}		0.79 ^{b}	0.75 ^{c}	0.85 ^{a}	
LSD $_{(0.05)}$	S = 0.0154	I = 0.0178	S × I = 0.0309		S = 0.02	I = 0.03	S × I = 0.05	

Means followed by the same letters are not significantly different from one another based on Duncan's protected LSD test ($p \leq 0.05$). NW is the control (nonmagnetic water or natural untreated water); NFT is the nutrient film technique hydroponic system.

4. Conclusions

Because of the recycling of fertigation, soilless culture systems (NFT, tower aeroponics, pyramidal aeroponics systems) can be effective tools for enhancing agricultural output and water productivity. The application of magnetic treatment to irrigation water improved the efficiency of soilless cultivation techniques, where applying magnetic treatment (especially level 3, or MWL 3) in NFT, tower aeroponic, and pyramidal aeroponic systems increased the yield and water productivity of the strawberry by 80.9% and 89% in the tower system, in the NFT system by 71.1% and 79.3%, respectively, and in the pyramidal system by 66.87% and 82%, respectively, compared to the non-treated irrigation water solution. In addition, the fertigation solution consumption by the plant reduced by 4.8%, 6%, and 4.8% in the NFT, tower, and pyramidal aeroponic systems, respectively. Moreover, as compared to the control, magnetic water treatment increased the number of leaves per plant, the stem diameter, and the leaf area. Fruit quality was also improved, including titratable acidity, total soluble solids, and fruit hardness. The use of magnetic water in the soilless cultivation method resulted in higher-quality agricultural products that were predicted to fulfill customer expectations, according to the findings. As a result, more soilless culture systems need to be evaluated to determine the utility of the magnetic treatment of irrigation water in crop yield generation. This technology could be recommended for farmers using soilless culture techniques and should be more intensively implemented on a wide scale to achieve more yield and a greater reduction in water consumption, also to support eco-agriculture.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/agriculture12060819/s1, Table S1: The influence of soilless culture systems, irrigation water magnetic treatments, and their interaction on some plant growth parameters.

Author Contributions: Formal analysis, writing, editing, and data curation, T.M.K.M.; funding acquisition, investigation and conceptualization, J.G.; supervision, methodology, and project administration, M.E.A.; resources, validation and visualization, M.K.; methodology, software, and formal analysis, E.W. writing—original draft preparation, methodology, collect the data, and data curation, W.E.-S. All authors have read and agreed to the published version of the manuscript.

Funding: This work was financially supported by the National Natural Science Foundation of China Program (No. 51975255), Jiangsu Agriculture Science and Technology Innovation Fund (CX (18) 3048), and the Project Funded by the Priority Academic Program Development of Jiangsu Higher Education Institution.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: All datasets used in this study are included in the manuscript and the Supplementary file.

Acknowledgments: We introduce our thanks to Agricultural Engineering Research Center, also Agriculture Engineering Department, Faculty of Agriculture, Cairo university for the big support to our team.

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

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