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# Water and fertilizer use efficiency of lettuce plants cultivated in soilless conditions under different irrigation systems

Eman Jarrar[a], A. Rasem Hasan[a,*], Abdallah Alimari[b], Mohammed Saleh[b]

*[a]Water and Environmental Studies Institute, An-Najah National University, P.O. Box 7, Nablus, Palestinian Authority, Tel. +970597511514; emails: mallah@najah.edu (A. Rasem Hasan), emanjarar2018@gmail.com (E. Jarrar)*
*[b]National Agricultural Research Center (NARC), Ministry of Agriculture, Jenin, Palestinian Authority, Tel. +972 599394855; email: omari_abd@yahoo.com (A. Alimari), Tel. +972 599132786; email: muh.saleh89@gmail.com (M. Saleh)*

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**ABSTRACT**

The lack of agricultural areas and limited access to water facilities forced the researchers to explore innovative water-efficient technologies in Palestine. This study aims at evaluating the biomass, water, and fertilizer use efficiency of soilless lettuce grown under two irrigation systems (surface drip irrigation (SDI) and responsive drip irrigation (RDI)). Two hundred lettuce seedlings were grown in a soilless system, where only the roots extend through standard channels filled with a mix of Peat moss, perlite, and vermiculite. The total number of lettuce plants harvested from the RDI system was 90 out of 100, while 66 out of 100 plants were harvested from the SDI system. RDI system had lower water consumption than SDI (340 vs. 440 L), with higher productivity (7.755 vs. 2.885 kg of lettuce). The water use efficiency in the RDI system was higher than in the SDI system (22.81 vs. 6.56 g/L). The RDI system improved the fertilizer use efficiency compared to the SDI system (10.34 vs. 3.85 kg/g). Soilless media with RDI has the potential for water-efficient and productive agricultural systems.

*Keywords:* Irrigation improvement; Crop management; Responsive drip irrigation "RDI"; Surface drip irrigation "SDI"

## 1. Introduction

In recent years, the population has grown significantly worldwide [1]. As a result of the population increase, the demand for clean and safe water has increased [2]. Developing industrial, agricultural, and commercial activities are associated with water in any country. In addition, the high living standards, desertification, and global warming formed water crises globally [3].

Palestine is affected by climatic conditions, and most parts are classified as arid and semi-arid areas [4]. Due to the Israeli occupation procedures for controlling more than 85% of the Palestinian water resources, a severe water crisis exists in Palestine. Palestine requires an additional 70 million m$^3$ of water per year to attain 50 m$^3$ of water per capita each year, which is the minimum requirement for primary water consumption [5]. Global climatic trends exhibit that the water crisis is foreseen to aggravate. It is shown that the water problems negatively affect cereal crop production in the MENA region, which suffers from the highest food deficits among all world regions [6]. One of the MENA regions is Palestine, where the agricultural sector is one of the most important and oldest economic sectors. Water uses for agricultural purposes were estimated to be 150 million m$^3$ annually (60 million cubic meters in the West Bank and the rest in the Gaza Strip) [7].

The most common farming type in Palestine is conventional agricultural practices. Unfortunately, the conventional type requires a large land area and suffers from high and inefficient water use. Besides, it yields high

* Corresponding author.

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concentrations of nutrients and pesticides in the runoff and soil degradation accompanied by erosion [8]. The lack of agricultural areas and the limited access to water facilities had complexed the situation in Palestine. Thus, water-efficient technologies should be developed to achieve water conservation and efficient water use and so improve local farming systems [9].

Hydroponic farming is a method of growing plants without soil requiring limited land and water. Hydroponics has become favored and is expected to play a significant role in future agriculture [10]. Several hydroponic systems have been developed and were commercially utilized successfully for crop production [11]. One of the most common examples is the soilless system, which provides plants with nutrients and water [12]. This system is highly productive and can address the shortage of land and water concerning the growing demand for food production [13]. Soilless systems contributed 11 times higher lettuce yields than conventional production [14]. In this context, the efficient uses of nutrients and water are significant, as the products' productivity and quality depend on the irrigation system [15]. The surface drip technique is the most common system for plant irrigation in the soilless channels. Surface drip irrigation (SDI) is the most common technique used, but responsive drip irrigation (RDI) has the attention because of the intermittent water supply for the plant [16]. In the RDI system, the plants self-regulate the delivery of water and nutrients by emitting root exudates into the surrounding environment. Besides, RDI could increase the yield of leafy crops and decrease energy consumption [17].

In terms of the problems related to the Palestinian agricultural sector, applying the hydroponic system was thought to overcome the land obstacles. This study aims to assess the hydroponic applicability in Palestine, identify the system's limitations, and provide solutions for product development. Also, drip irrigation systems are promising solutions to face the water scarcity in Palestine. In this context, this study evaluates the biomass, water, and fertilizer use efficiency of soilless lettuce grown under two irrigation systems (SDI and RDI) in Palestine. The study can help decision-makers amend the current agriculture system of irrigations works and change it to suit the situation of farmers and their needs, thus contributing to enhancing farmers' financial concerns and conserving irrigation water.

## 2. Material and method

### 2.1. Experiment description and design

This study was conducted in a greenhouse with an orientation of north–south at the National Agriculture Research Center (NARC) in Jenin, Palestine (N00204013, E00179776), with an average temperature (20°C–25°C) and humidity (70%) from June to November 2020. Lettuce seedlings were grown in a soilless system consisting of two standard channels, each 6 m in length, 5 cm in depth, and 10 cm in width (Fig. 1). Channels were filled with a mix-media of Peat moss, perlite, and vermiculite. Two hundred plants were grown in the system with a 30 cm spacing distance. The cultivated plants were irrigated with two different irrigation techniques; surface drip irrigation (SDI) and responsive drip irrigation (RDI), with one hundred plants grown in each irrigation system. The complete randomized block design was used to plan the experiment (2 × 3 replicates for each irrigation system).

The surface drip irrigation system consisted of a plastic pipe (0.5 inches) with a 30 cm distance between drippers and delivered a flowrate of around 8 L/h per dripper. Responsive drip irrigation of Grow Stream was employed in creating a symbiotic relationship between plant roots, media, and water. In the RDI system, the plants self-regulate the delivery of water and nutrients by emitting root exudates into the surrounding environment. The pipes were placed on a slight decline (1%–3%), generally at bench height.

The nutrient solution was added to 120 L of water in a plastic tank for each irrigation system. The nutrients used in the experiment were 750 g of fertilizer with 13%–13%–13% as N, $P_2O_5$, and $K_2O$, respectively, 20 g of iron granules (EDDHA-Fe-6%), and 20 mm calcium (Habical. Ca s). Both irrigation systems were operated as a closed cycle; the surplus nutrients were recovered after use and then recycled through the system. The experiment was monitored daily to ensure the plant needs such as; water, nutrients, and insecticide were available.

### 2.2. Samples collection and analysis

For analysis purposes, one from every five-lettuce plants was randomly selected. Also, the same sampling method

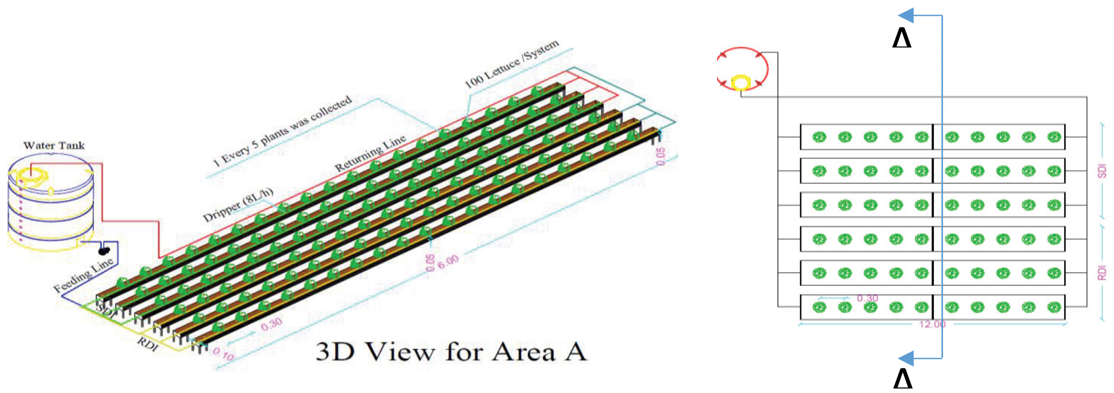


Fig. 1. Schematic diagram of the experiment. All dimensions are in m.

was utilized for the growing media. The total analyzed samples were 40 plants and 40 growing media. The analyses of samples were done before, during, and at the end of the cultivation experiment (referred as "after" later on in the results section). Total nitrogen (N), organic phosphorus (P), potassium (K), and calcium (Ca) were determined in both plant and media according to the international center for agricultural research in the dry areas (ICARDA) protocol [18]. The grown media were tested additionally for electrical conductivity (EC) and pH.

The consumed water volumes were measured for both irrigation systems (SDI and RDI) and for both the feeding water and the drained water. Plants' consumed water was calculated based on Eq. (1).

$$\text{Total water used} = \text{System input water} - \text{Total drained water} \quad (1)$$

The collected lettuce plants from each channel were gathered and weighted to determine the total productivity in each channel. The total productivity was divided by the water used in the proposed channel to define the water use efficiency (WUE) in kg fresh weight/L according to Eq. (2) [19].

$$\text{WUE} = \frac{\text{Total productivity produced}\left(\text{kg / channel}\right)}{\text{Total water used}\left(\text{liter / channel}\right)} \quad (2)$$

### 2.3. Statistical analysis

Percentage change (% change) and mean for numerical data, in addition to repeated ANOVA measure (*F*-test), were employed to compare the SDI to the RDI utilizing Mauchly's test. The pairwise comparisons were used to compare media and plant leaf contents at the three stages; before, during, and after the experiment. *Z*-test for two proportions was used to test statistical differences between the two proportions with a confidence level of 95% ($P \leq 0.05$) by using SPSS V25.

## 3. Results

### 3.1. Media contents of the SDI and RDI systems

The changes in the total nitrogen (N), organic phosphorus (P), calcium (Ca), potassium (K), pH, and EC in the media of both systems (SDI and RDI) at the three stages: before, during, and after the experiment, were tracked (Fig. 2) and statistically analyzed (Tables 1–6).

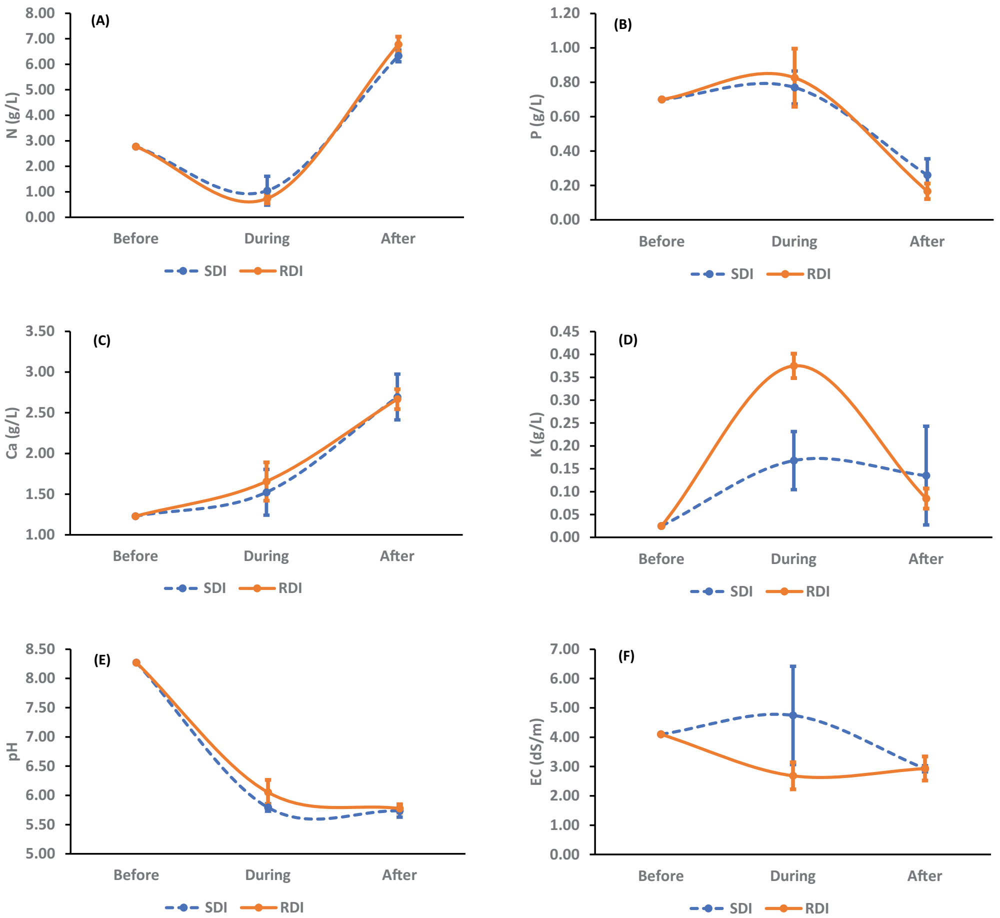


Fig. 2. The change in the media before, during, and after the experiment in terms of (A) nitrogen, (B) organic phosphorus, (C) calcium, (D) potassium, (E) pH, and (F) EC.

Table 1
Statistical analysis for media N-levels in both SDI and RDI systems of the experiment

| Media N-levels (g/L) | | Irrigation systems Mean ± SD | | Statistical test* | | | |
|---|---|---|---|---|---|---|---|
| | | SDI ($n$ = 3) | RDI ($n$ = 3) | % Change | $F$ | $P$-value | Effect size |
| N (Before) | | 2.77 ± 0.0 | 2.77 ± 0.0 | 0.0[d] | 0.190 | 0.685 | 0.045 |
| N (During) | | 1.04 ± 0.565 | 0.74 ± 0.19 | –29.39[e] | | | |
| N (After or harvested) | | 6.33 ± 0.23 | 6.78 ± 0.3 | 7.11[f] | | | |
| | % Change | –62.45[a] | –73.29[a] | | | | |
| | | 128.52[b] | 144.77[b] | | | | |
| | | 508.65[c] | 816.22[c] | | | | |
| Statistical test[€] | Mauchly's test of sphericity | 0.234 | | | | | |
| | $F$ | 3,864.141 | | | | | |
| | $P$-value | <0.001* | | | | | |
| | Size effect | 0.999 | | | | | |
| | Pairwise comparisons ($P$-value) | <0.001*[a] | | | | | |
| | | <0.001*[b] | | | | | |
| | | <0.001*[c] | | | | | |

*Significant at $P \leq 0.05$; $P > 0.05$: Not significant; N: nitrogen; $n$: number of planting basins; SD: standard deviation; $F$: repeated ANOVA measures; Pairwise comparisons (LSD)[a]: Before vs. During; [b]: Before vs. After; [c]: During vs. After; [d]: % change in SDI vs. RDI media before the experiment; [e]: % change in SDI vs. RDI media, and [f]: % change in SDI vs. RDI media after the experiment, [€]Statistical test between SDI and RDI systems.

Table 2
Statistical analysis for media P-levels in both SDI and RDI systems of the experiment

| Media P-levels (g/L) | | Irrigation systems Mean ± SD | | Statistical test* | | | |
|---|---|---|---|---|---|---|---|
| | | Surface ($n$ = 3) | RDI ($n$ = 3) | % Change | $F$ | $P$-value | Effect size |
| P (Before) | | 0.70 ± 0.0 | 0.70 ± 0.0 | 0.00[d] | 0.194 | 0.682 | 0.046 |
| P (During) | | 0.77 ± 0.095 | 0.826 ± 0.169 | 7.32[e] | | | |
| P (After or harvested) | | 0.26 ± 0.095 | 0.167 ± 0.045 | –35.9[f] | | | |
| | % Change | 10.0[a] | 18.0[a] | | | | |
| | | –62.86[b] | –76.14[b] | | | | |
| | | –66.23[c] | –79.78[c] | | | | |
| Statistical test[€] | Mauchly's test of sphericity | 0.074 | | | | | |
| | $F$ | 1,659.073 | | | | | |
| | $P$-value | <0.001* | | | | | |
| | Size effect | 0.998 | | | | | |
| | Pairwise comparisons ($P$-value) | 0.154[a] | | | | | |
| | | <0.001*[b] | | | | | |
| | | 0.002*[c] | | | | | |

*Significant at $P \leq 0.05$; $P > 0.05$: Not significant; P: organic phosphorous; $n$: number of planting basins; SD: standard deviation; $F$: repeated ANOVA measures; Pairwise comparisons (LSD)[a]: Before vs. During; [b]: Before vs. After; [c]: During vs. After; [d]: % change in SDI vs. RDI media before the experiment; [e]: % change in SDI vs. RDI media, and [f]: % change in SDI vs. RDI media after the experiment, [€]Statistical test between SDI and RDI systems.

Nitrogen had values of 2.77 ± 0, 1.04 ± 0.57, and 6.33 ± 0.23 g/L for SDI and 2.77 ± 0, 0.74 ± 0.19, and 6.78 ± 0.3 g/L for RDI in the media before, during, and after, respectively (Fig. 2A). The nitrogen concentration decreased (the percentage of change was –62.45% for SDI and –73.29% for RDI) during the cultivation experiment. Then it increased at the end of the experiment (the change percentage between the start and the end point

Table 3
Statistical analysis for media Ca-levels in both SDI and RDI systems of the experiment

| Media Ca-levels (g/L) | | Irrigation systems Mean ± SD | | Statistical test* | | | |
|---|---|---|---|---|---|---|---|
| | | SDI ($n$ = 3) | RDI ($n$ = 3) | % Change | $F$ | $P$-value | Effect size |
| Ca (Before) | | 1.23 ± 00 | 1.23 ± 00 | 0.00[d] | 0.243 | 0.648 | 0.057 |
| Ca (During) | | 1.52 ± 0.28 | 1.66 ± 0.24 | 8.75[e] | | | |
| Ca (After or harvested) | | 2.69 ± 0.28 | 2.67 ± 0.12 | –0.99[f] | | | |
| | | 23.85[a] | 34.69[a] | | | | |
| | % Change | 118.97[b] | 116.80[b] | | | | |
| | | 76.81[c] | 60.97[c] | | | | |
| Statistical test[€] | Mauchly's test of sphericity | 0.286 | | | | | |
| | $F$ | 2,586.084 | | | | | |
| | $P$-value | <0.001* | | | | | |
| | Size effect | 0.998 | | | | | |
| | Pairwise comparisons ($P$-value) | 0.027*[a] | | | | | |
| | | <0.001*[b] | | | | | |
| | | 0.003*[c] | | | | | |

*Significant at $P \leq 0.05$; $P > 0.05$: Not significant; Ca: calcium; $n$: number of planting basins; SD: standard deviation; $F$: repeated ANOVA measures; Pairwise Comparisons (LSD)[a]: Before vs. During; [b]: Before vs. After; [c]: During vs. After; [d]: % change in SDI vs. RDI media before the experiment; [e]: % change in SDI vs. RDI media, and [f]: % change in SDI vs. RDI media after the experiment, [€]Statistical test between SDI and RDI systems.

Table 4
Statistical analysis for media K-levels in both SDI and RDI systems of the experiment

| Media K-levels (g/L) | | Irrigation systems Mean ± SD | | Statistical test* | | | |
|---|---|---|---|---|---|---|---|
| | | SDI ($n$ = 3) | RDI ($n$ = 3) | % Change | $F$ | $P$-value | Effect size |
| K (Before) | | 0.025 ± 0 | 0.025 ± 0 | 0.00[d] | 50.510 | 0.002 | 0.927 |
| K (During) | | 0.168 ± 0.012 | 0.375 ± 0.027 | 123.21[e] | | | |
| K (After or harvested) | | 0.135 ± 0.023 | 0.085 ± 0.022 | –37.04[f] | | | |
| | | 572.00[a] | 1,400.00[a] | | | | |
| | % Change | 440.00[b] | 240.00[b] | | | | |
| | | –19.64[c] | –77.33[c] | | | | |
| Statistical test[€] | Mauchly's test of sphericity | 0.438 | | | | | |
| | $F$ | 1,354.445 | | | | | |
| | $P$-value | <0.001** | | | | | |
| | Size effect | 0.997 | | | | | |
| | Pairwise comparisons ($P$-value) | 0.000*[a] | | | | | |
| | | 0.001*[b] | | | | | |
| | | <0.001*[c] | | | | | |

*Significant at $P \leq 0.05$; $P > 0.05$: Not significant; K: potassium; $n$: number of planting basins; SD: standard deviation; F: repeated ANOVA measures; Pairwise Comparisons (LSD)[a]: Before vs. During; [b]: Before vs. After; [c]: During vs. After; [d]: % change in SDI vs. RDI media before the experiment; [e]: % change in SDI vs. RDI media, and [f]: % change in SDI vs. RDI media after the experiment, [€]Statistical test between SDI and RDI systems.

reached 128.52% for SDI and 144.77% for RDI). According to the statistical results, the differences between the nitrogen levels at all experimental times were statistically significant for both irrigation systems, with a size effect of 99.9% ($F$ = 3864.141, $P$ < 0.001). The Pairwise Comparisons test (least square difference (LSD)) in repeated ANOVA measures confirmed the significance (Table 1).

The P-levels were also determined (Fig. 2B) for SDI were 0.7 ± 0, 0.77 ± 0.095, and 0.26 ± 0.095 g/L. While for RDI, the P-levels had values of 0.7 ± 0, 0.826 ± 0.169, and

Table 5
Statistical analysis for media pH levels in both SDI and RDI systems of the experiment

| Media pH levels | | Irrigation systems Mean ± SD | | Statistical test* | | | |
|---|---|---|---|---|---|---|---|
| | | SDI ($n$ = 3) | RDI ($n$ = 3) | % Change | $F$ | $P$-value | Effect size |
| pH (Before) | | 8.27 ± 0.0 | 8.27 ± 0.0 | 0.00[d] | 3.342 | 0.142 | 0.455 |
| pH (During) | | 5.79 ± 0.06 | 6.05 ± 0.21 | 4.49[e] | | | |
| pH (After or harvested) | | 5.74 ± 0.11 | 5.78 ± 0.07 | 0.7[f] | | | |
| | | –29.99[a] | –26.84[a] | | | | |
| | % Change | –30.59[b] | –30.11[b] | | | | |
| | | –0.86[c] | –4.46[c] | | | | |
| | Mauchly's test of sphericity | 0.568 | | | | | |
| Statistical test€ | $F$ | 59,109.282 | | | | | |
| | $P$-value | <0.001* | | | | | |
| | Size effect | 1.000 | | | | | |
| | Pairwise comparisons ($P$-value) | <0.001*[a] | | | | | |
| | | <0.00*[b] | | | | | |
| | | 0.059[c] | | | | | |

*Significant at $P \leq 0.05$; $P > 0.05$: Not significant; $n$: number of planting basins; SD: standard deviation; $F$: repeated ANOVA measures; Pairwise Comparisons (LSD)[a]: Before vs. During; [b]: Before vs. After; [c]: During vs. After; [d]: % change in SDI vs. RDI media before the experiment; [e]: % change in SDI vs. RDI media, and [f]: % change in SDI vs. RDI media after the experiment, €Statistical test between SDI and RDI systems.

Table 6
Statistical analysis for media EC-levels in both SDI and RDI systems of the experiment

| Media EC levels (dS/m) | | Irrigation systems Mean ± SD | | Statistical test* | | | |
|---|---|---|---|---|---|---|---|
| | | SDI ($n$ = 3) | RDI ($n$ = 3) | % Change | $F$ | $P$-value | Effect size |
| EC (Before) | | 4.1 ± 0 | 4.1 ± 0 | 0.00[d] | 3.224 | 0.147 | 0.446 |
| EC (During) | | 4.74 ± 1.67 | 2.69 ± 0.46 | –43.36[e] | | | |
| EC (After or harvested) | | 2.92 ± 0.11 | 2.93 ± 0.41 | 0.34[f] | | | |
| | | 15.61[a] | –34.39[a] | | | | |
| | % Change | –28.78[b] | –28.54[b] | | | | |
| | | –38.4[c] | 8.92[c] | | | | |
| | Mauchly's test of sphericity | 0.062 | | | | | |
| Statistical test€ | $F$ | 355.333 | | | | | |
| | $P$-value | <0.001* | | | | | |
| | Size effect | 0.989 | | | | | |
| | Pairwise comparisons ($P$-value) | 0.485[a] | | | | | |
| | | 0.00*[b] | | | | | |
| | | 0.159[c] | | | | | |

*Significant at $P \leq 0.05$; $P > 0.05$: Not significant; EC: electrical conductivity; $n$: number of planting basins; SD: standard deviation; F: repeated ANOVA measures; Pairwise Comparisons (LSD)[a]: Before vs. During; [b]: Before vs. After; [c]: During vs. After; [d]: % change in SDI vs. RDI media before the experiment; [e]: % change in SDI vs. RDI media, and [f]: % change in SDI vs. RDI media after the experiment, €Statistical test between SDI and RDI systems.

0.167 ± 0.045 g/L before, during, and after the cultivation, respectively. For both systems, the P-levels decreased at the end of the experiment. The results showed a decline in the P-levels in SDI and RDI by –62.86% and –76.14%, respectively. The pairwise Comparisons test (LSD) demonstrated that there was a statistically significant difference before and after the experiment in both SDI and RDI systems ($P < 0.001$). Also, the P-level change during the experiment and at the end was statistically significant ($P = 0.002$), as shown in Table 2.

Fig. 2C presents the changes in the calcium levels in the media for SDI and RDI. Accordingly, the calcium concentrations increased by 118.97% for SDI and 116.80% for RDI at the end of the experiment. The mean Ca-level increased from 1.23 ± 00 to 2.69 ± 0.28 g/L for SDI. For RDI, Ca-levels in media were 1.23 ± 00, 1.66 ± 0.24, and 2.67 ± 0.12 g/L before, during, and after, respectively. Repeated ANOVA measures pointed out that there were statistically significant trends in media calcium levels before, during, and after lettuce plants were grown in both irrigation systems (SDI and RDI), and the size effect was 99.8% ($F = 2586.084$, $P < 0.001$). The Pairwise Comparisons test (LSD) revealed that the differences in Ca-levels before lettuce cultivation compared to during and after the experiment were statistically significant in both SDI and RDI systems (Table 3).

The media K-levels of SDI and RDI systems are illustrated in Fig. 2D. The level of K in the media increased with the cultivation and decreased at the end of the experiment. The mean media K-levels were 0.025 ± 0, 0.168 ± 0.012, and 0.135 ± 0.023 g/L for SDI. For RDI, the levels had values of 0.025 ± 0, 0.375 ± 0.027, and 0.085 ± 0.022 g/L before, during, and after, respectively. The changes in percentages between the before and during were 572% for SDI and 1,400% for RDI. At the same time, the percentages decreased to 440% and 240% for SDI and RDI before and after the experiment. Table 3 shows that there were statistically significant trends in media K-levels before, during, and after lettuce plants were grown in both irrigation systems (SDI and RDI), and the size effect was 0.927% ($F = 1,354.445$, $P < 0.001$). The Pairwise Comparison test (LSD) indicated a statistically significantly different before lettuce cultivation compared to during and after in both SDI and RDI systems ($P < 0.001$ and $P = 0.001$, respectively).

The pH of the media decreased sharply for both systems. The mean values of pH media changed from 8.27 ± 0 (before) to 5.79 ± 0.06 and 6.05 ± 0.21 (during). The media pH reached 5.74 ± 0.11 and 5.78 ± 0.07 0 at the end of the experiment for SDI and RDI, respectively (Fig. 2E). The changes in media pH levels were –29.99% and –26.84% between before and during the experiment in SDI and RDI, respectively. However, the percentages change in media pH levels were –30.59% and –30.11% between before and after lettuce plants growing in SDI and RDI, respectively. The pairwise comparisons test (LSD) revealed a significant difference between the pH of the media before/during and before/after lettuce growing in both SDI and RDI systems ($P < 0.001$ and $P < 0.001$, respectively). In contrast, there is no statistically significant difference in media pH levels during the cultivation compared to after lettuce plants were grown in both SDI and RDI systems ($P = 0.059$) (Table 5).

Fig. 2F shows the change in the media EC for both irrigation systems. Accordingly, the mean levels of media EC values were 4.1 ± 0, 4.74 ± 1.67, and 2.92 ± 0.11 ms for SDI, and 4.1 ± 0, 2.69 ± 0.46, and 2.93 ± 0.41 ms for RDI before, during and after the experiment, respectively. According to Table 6, the repeated ANOVA test indicated significant differences in media EC-levels before, during, and after the experiment in both irrigation systems (SDI and RDI), and the size effect was 98.9% ($F = 355.333$, $P < 0.001$). The pairwise comparisons test (LSD) for EC levels in the media showed statistically significantly different before and after cultivation in both SDI and RDI systems (Table 6). However, there was no statistically significant difference in media EC levels during lettuce growing compared to before and after in SDI and RDI systems ($P = 0.485$ and $P = 0.159$, respectively).

### *3.2. Lettuce leaves' content grown in the SDI and RDI systems*

The changes in the total nitrogen (N), organic phosphorus (P), calcium (Ca), and potassium (K) in the lettuce plant leaves were measured and statistically analyzed before, during, and at the end of the experiment. Fig. 3 shows the changes in the plant leaves for the SDI and The RDI systems.

For the lettuce leaves, the nitrogen content had gradually increased from 3.32 ± 0 to 4.16 ± 0.513 g/L for SDI and 4.047 ± 0.225 g/L for RDI. During the experiment, the nitrogen levels in SDI and RDI were 3.84 ± 0.488 and 3.72 ± 0.269, respectively (Fig. 3A). The percentage of changes before and after for the N-levels in the SDI and RDI were 25.3% and 21.9%, respectively. The repeated ANOVA test revealed statistically significant differences in leaves' N-levels before, during, and after the experiment in both irrigation systems (Table 7). The size effect was 99.9% ($F = 6968.736$, $P < 0.001$). The pairwise comparison test (LSD) indicated that the differences between the before/during and before/after were statistically significant in both SDI and RDI systems ($P = 0.046$, $P = 0.008$, respectively).

The P-levels in the leaves were also determined and shown in Fig. 3B. The P-levels increased from 0.49 g/L to 1.06 g/L during the experiment for the SDI system. For the RDI system, the P-levels decreased during the experiment to reach 0.47 g/L. The final P-levels were 1.018 g/L and 0.533 g/L in the SDI and RDI, respectively. The statistical analysis for the P content of the leaves of lettuce plants grown in the SDI and RDI systems is illustrated in Table 8. The statistical test (repeated ANOVA measures) showed that there were statistically significant differences in P-levels before, during, and after lettuce plants were grown in both SDI and RDI, with a size effect of 99.8% ($F = 1658.491$, $P < 0.001$). The Pairwise Comparisons test (LSD) statistical analysis demonstrated that the differences between before/during and before/after the experiment were statistically significant for both SDI and RDI systems ($P = 0.006$, $P = 0.003$, respectively). In contrast, there was no statistically significant difference in P-levels at the end of the experiment and for both SDI and RDI systems ($P = 0.902$).

The Ca-levels in the plants' leaves increased during the experiment and decreased by the end (Fig. 3C). The mean Ca-levels of lettuce leaves changed as 1.89 ± 0, 2.84 ± 0.17, and 1.87 ± 0.33 g/L for SDI and 1.89 ± 0, 3.25 ± 0.53, and 1.68 ± 0.29 g/L for RDI in before, during and after the experiment, respectively. The statistical test pointed out there were statistically significant differences in Ca-levels before, during, and after lettuce plants were grown in both irrigation systems (SDI and RDI), and the size effect was 99.6% ($F = 945.358$, $P < 0.001$). In the SDI and RDI systems, the pairwise comparisons test (LSD) exhibited statistically significant differences during the experiment compared to before and after lettuce plants were grown ($P = 0.002$,

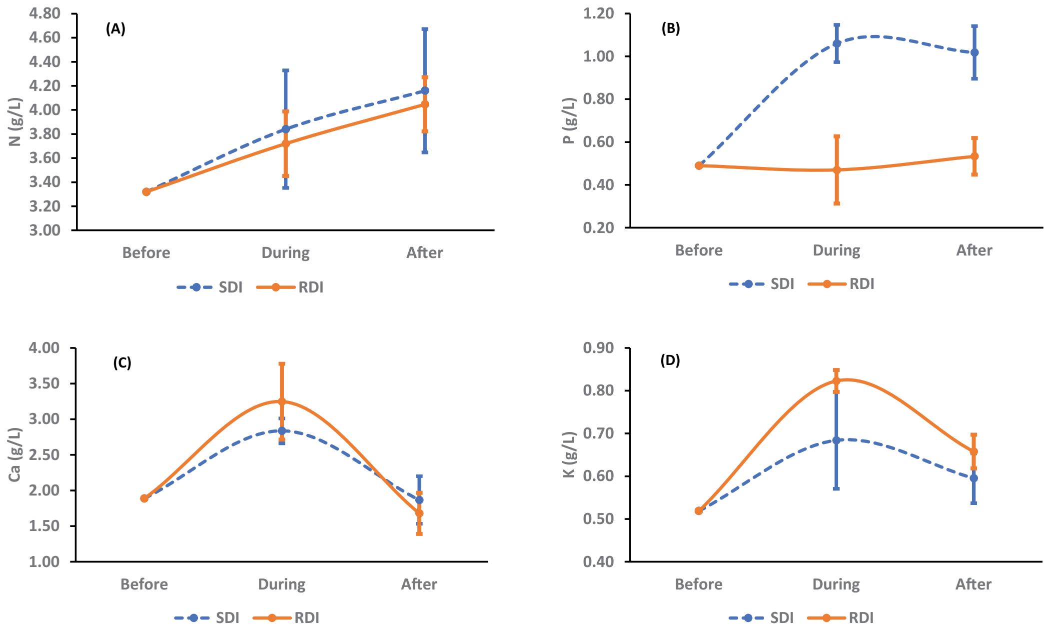


Fig. 3. The change in the lettuce leaves content before, during, and after the experiment in terms of (A) nitrogen, (B) organic phosphorus, (C) calcium, and (D) potassium.

Table 7
Statistical analysis of N-levels in the leaves of lettuce plants grown in the SDI and RDI systems

| N-levels in lettuce leaves (g/L) | | Irrigation systems Mean ± SD | | Statistical test* | | | |
|---|---|---|---|---|---|---|---|
| | | SDI ($n$ = 3) | RDI ($n$ = 3) | % Change | $F$ | $P$-value | Effect size |
| N (Before) | | 3.32 ± 0.0 | 3.32 ± 0.0 | 0.00[d] | 0.756 | 0.434 | 0.159 |
| N (During) | | 3.84 ± 0.488 | 3.72 ± 0.269 | –3.13[e] | | | |
| N (After or harvested) | | 4.16 ± 0.513 | 4.047 ± 0.225 | –2.72[f] | | | |
| | % Change | 15.66[a] | 12.05[a] | | | | |
| | | 25.3[b] | 21.9[b] | | | | |
| | | 8.33[c] | 8.79[c] | | | | |
| Statistical test€ | Mauchly's test of sphericity | 0.120 | | | | | |
| | $F$ | 6,968.736 | | | | | |
| | $P$-value | *<0.001 | | | | | |
| | Size effect | 0.999 | | | | | |
| | Pairwise comparisons ($P$-value) | 0.046[a] | | | | | |
| | | 0.008[b] | | | | | |
| | | 0.332[c] | | | | | |

*Significant at $P \leq 0.05$; $P > 0.05$: Not significant; P: organic phosphorous; $n$: number of planting basins; SD: standard deviation; F: repeated ANOVA measures; Pairwise Comparisons (LSD)[a]: Before vs. During; [b]: Before vs. After; [c]: During vs. After; [d]: % change in SDI vs. RDI for lettuce leaves before the experiment; [e]: % change in SDI vs. RDI lettuce leaves, and [f]: % change in SDI vs. RDI for lettuce leaves after the experiment, €Statistical test between SDI and RDI systems for lettuce leaves.

$P$ = 0.003, respectively). In contrast, there was no statistically significant difference in the calcium-levels before the cultivation compared to after lettuce plants were grown in the SDI and RDI systems ($P$ = 0.411), as shown in Table 9.

Fig. 3D illustrates lettuce plant K content of leaves for both the SDI and RDI systems. Accordingly, the values of the mean K-levels were 0.519 ± 0, 0.684 ± 0.114, and 0.595 ± 0.058 g/L for SDI. For RDI, the K-levels had values of 0.519 ± 0, 0.823 ± 0.026, and 0.658 ± 0.039 g/L before, during, and after the experiment, respectively. The repeated ANOVA test (Table 10) indicated statistically significant differences in leaf lettuce plant K-levels before,

Table 8
Statistical analysis of P-levels in the leaves of lettuce plants grown in the SDI and RDI systems

| P-levels in lettuce leaves (g/L) | | Irrigation systems Mean ± SD | | Statistical test* | | | |
|---|---|---|---|---|---|---|---|
| | | SDI ($n$ = 3) | RDI ($n$ = 3) | % Change | $F$ | $P$-value | Effect size |
| P (Before) | | 0.49 ± 0.0 | 0.49 ± 0.0 | 0[d] | 116.124 | <0.001* | 0.967 |
| P (During) | | 1.06 ± 0.087 | 0.47 ± 0.157 | –55.66[e] | | | |
| P (After or harvested) | | 1.018 ± 0.123 | 0.533 ± 0.085 | –47.61[f] | | | |
| | % Change | 116.33[a] | –4.08[a] | | | | |
| | | 107.76[b] | 8.78[b] | | | | |
| | | –3.96[c] | 13.4[c] | | | | |
| Statistical test[€] | Mauchly's test of sphericity | 0.233 | | | | | |
| | $F$ | 1,658.491 | | | | | |
| | $P$-value | <0.001* | | | | | |
| | Size effect | 0.998 | | | | | |
| | Pairwise comparisons ($P$-value) | 0.006*[a] | | | | | |
| | | 0.003*[b] | | | | | |
| | | 0.902[c] | | | | | |

*Significant at $P \leq 0.05$; $P > 0.05$: Not significant; P: organic phosphorous; $n$: number of planting basins; SD: standard deviation; F: repeated ANOVA measures; Pairwise Comparisons (LSD)[a]: Before vs. During; [b]: Before vs. After; [c]: During vs. After; [d]: % change in SDI vs. RDI for lettuce leaves before the experiment; [e]: % change in SDI vs. RDI lettuce leaves, and [f]: % change in SDI vs. RDI for lettuce leaves after the experiment, [€]Statistical test between SDI and RDI systems for lettuce leaves.

Table 9
Statistical analysis of Ca-levels in the leaves of lettuce plants grown in the SDI and RDI systems

| Ca-levels in lettuce leaves (g/L) | | Irrigation systems Mean ± SD | | Statistical test[£] | | | |
|---|---|---|---|---|---|---|---|
| | | SDI ($n$ = 3) | RDI ($n$ = 3) | % Change | $F$ | $P$-value | Effect size |
| Ca (Before) | | 1.89 ± 0.0 | 1.89 ± 0.0 | 0.0[d] | 0.262 | 0.636 | 0.062 |
| Ca (During) | | 2.84 ± 0.17 | 3.25 ± 0.53 | 14.45[e] | | | |
| Ca (After or harvested) | | 1.87 ± 0.33 | 1.68 ± 0.29 | –10[f] | | | |
| | % Change | 50.26[a] | 71.96[a] | | | | |
| | | –1.06[b] | –11.11[b] | | | | |
| | | –34.15[c] | –48.31[c] | | | | |
| Statistical test[€] | Mauchly's test of sphericity | 0.706 | | | | | |
| | $F$ | 945.358 | | | | | |
| | $P$-value | 0.000 | | | | | |
| | Size effect | 0.996 | | | | | |
| | Pairwise comparisons ($P$-value) | 0.002*[a] | | | | | |
| | | 0.411[b] | | | | | |
| | | 0.003*[c] | | | | | |

*Significant at $P \leq 0.05$; $P > 0.05$: Not significant; Ca: calcium; $n$: number of planting basins; SD: standard deviation; F: repeated ANOVA measures; Pairwise Comparisons (LSD)[a]: Before vs. During; [b]: Before vs. After; [c]: During vs. After; [d]: % change in SDI vs. RDI for lettuce leaves before the experiment; [e]: % change in SDI vs. RDI lettuce leaves, and [f]: % change in SDI vs. RDI for lettuce leaves after the experiment, [€]Statistical test between SDI and RDI systems for lettuce leaves.

during, and after the cultivation experiment in both irrigation systems (SDI and RDI), and the size effect was 99.7% ($F$ = 1386.15, $P$ < 0.001). Also, the pairwise comparisons test (LSD) proved statistically significant differences between before/during and before/after the experiment ($P$ = 0.002, $P$ = 0.006, respectively). Also, there is a statistically significant difference in leaves K-levels during the experiment compared to after ($P$ = 0.004).

Table 10
Statistical analysis of K-levels in the leaves of lettuce plants grown in the SDI and RDI systems.

| K-levels in lettuce leaves (g/L) | | Irrigation systems Mean ± SD | | Statistical test* | | | |
|---|---|---|---|---|---|---|---|
| | | SDI ($n$ = 3) | RDI ($n$ = 3) | % Change | $F$ | $P$-value | Effect size |
| K (Before) | | 0.519 ± 0 | 0.519 ± 0 | 0.00[d] | 3.883 | 0.120 | 0.493 |
| K (During) | | 0.684 ± 0.114 | 0.823 ± 0.026 | 20.27[e] | | | |
| K (After or harvested) | | 0.595 ± 0.058 | 0.658 ± 0.039 | 10.47[f] | | | |
| | % Change | 31.79[a] | 58.57[a] | | | | |
| | | 14.64[b] | 26.78[b] | | | | |
| | | –13.01[c] | –20.05[c] | | | | |
| Statistical test[€] | Mauchly's test of sphericity | 0.398 | | | | | |
| | $F$ | 1,386.150 | | | | | |
| | $P$-value | <0.001* | | | | | |
| | Size effect | 0.997 | | | | | |
| | Pairwise comparisons ($P$-value) | 0.002*[a] | | | | | |
| | | 0.006*[b] | | | | | |
| | | 0.004*[c] | | | | | |

*Significant at $P \leq 0.05$; $P > 0.05$: Not significant; K: potassium; $n$: number of planting basins; SD: standard deviation; F: repeated ANOVA measures; Pairwise Comparisons (LSD)[a]: Before vs. During; [b]: Before vs. After; [c]: During vs. After; [d]: % change in SDI vs. RDI for lettuce leaves before the experiment; [e]: % change in SDI vs. RDI lettuce leaves, and [f]: % change in SDI vs. RDI for lettuce leaves after the experiment, [€]Statistical test between SDI and RDI systems for lettuce leaves.

Table 11
Water and fertilizers use efficiencies of soilless lettuce plants grown under SDI and RDI

| Parameters | Irrigation systems | | | | Statistical test | | |
|---|---|---|---|---|---|---|---|
| | SDI ($n$ = 100) | RDI ($n$ = 100) | % of Total | | | | |
| | | | SDI | RDI | % Change | $Z$-test | $P$-value |
| Numbers of harvested plants' leaves | 66 | 90 | 42.31 | 57.69 | 36.36 | 2.175 | 0.015 |
| Water consumed (L) | 440 | 340 | 56.41 | 43.59 | –22.73 | –1.813 | 0.035 |
| Productivity (g) | 2,885 | 7,755 | 27.11 | 72.89 | 168.80 | 6.474 | <0.001 |
| Productivity/ plant ratio (g) | 43.71 | 86.17 | 33.65 | 66.35 | 97.14 | 4.625 | <0.001 |
| Water use efficiency (g/L) | 6.56 | 22.81 | 22.33 | 77.67 | 247.86 | 7.826 | <0.001 |
| Fertilizer use efficiency (kg/g) | 3.85 | 10.34 | 27.11 | 72.89 | 168.80 | 6.474 | <0.001 |

*Significant at $P \leq 0.05$; $P > 0.05$: Not significant; and $n$: number of plants.

### 4.3. Water and fertilizers use efficiency of soilless lettuce plants grown in the SDI and RDI systems

The efficiency of cultivation of lettuce plants in the soilless media using SDI and RDI systems was assessed. In this context, 200 lettuce plants were grown (100 for each system). The total number of lettuce plants harvested from the RDI system was 90, while only 66 were gathered from the SDI (Table 11).

The harvested proportion from the RDI system was statistically with higher significance levels than the SDI system (57.69% vs. 42.31%, respectively, % change = 36.36%, $Z$-test = 2.175, and $P$ = 0.015, Fig. 4A). The RDI system had lower water consumption (340 L) than the SDI (440 L). The $Z$-test revealed that the RDI system was statistically with lower significance levels than the SDI system regarding the consumed water during the experiment (43.59%, vs. 56.41% respectively, % change = –22.73%, $Z$-test = –1.813 and $P$ = 0.035, Fig. 4B). The productivity of the RDI system was higher than the SDI system (7.755 vs. 2.885 kg, respectively). The statistical test showed that the RDI system was higher statistically significant in productivity than the SDI system (72.89%vs. 27.11., respectively, % change = 168.8%, $Z$-test = 6.474 and $P$ < 0.001; Fig. 4C). The productivity per plant ratio exhibited that RDI system were higher statistically significant (66.35% vs. 33.65%, respectively, % change = 97.14%, $Z$-test = 4.625 and $P$ < 0.001; Fig. 4D). Additionally, the water use efficiency in the RDI system was larger than the SDI system (22.81 vs. 6.56 g/L, respectively). In this term, the $Z$-test illustrated that the

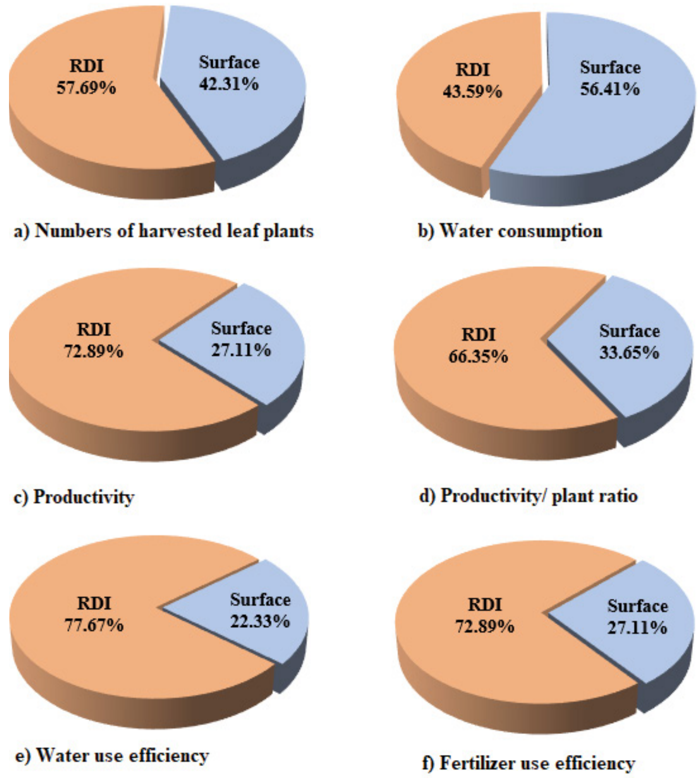


Fig. 4. Efficiency of soilless lettuce plants grown in the RDI and SDI systems in terms of (A) numbers of harvested leaves, (B) water consumption, (C) productivity, (D) productivity/plant ratio, (E) water use efficiency, and (F) fertilizer use efficiency.

Table 12
Shoot content of nutrients

| Nutrient | Shoot content of nutrients (g/kg) | |
|---|---|---|
| | SDI | RDI |
| N | 20.94 | 20.37 |
| P | 5.12 | 2.68 |
| K | 3.00 | 3.3 |
| Ca | 9.41 | 8.46 |

water use efficiency in the RDI system was higher statistically significant than in the SDI system (77.67% vs. 22.33%, % change = 247.86%, $Z$-test = 7.826 and $P < 0.001$; Fig. 4E). Finally, RDI improved the fertilizer use efficiency compared to the SDI system (10.34 vs. 3.85 kg/g). The statistical test showed that the fertilizer use efficiency in the RDI system was higher statistically significant than SDI system (27.11% vs. 72.89%, % change = 168.8%, $Z$-test = 6.474 and $P = 0.001$; Fig. 4F).

## 4. Discussion

In this study, lettuce plants were successfully cultivated in a hydroponic system in Palestine. The RDI system was compared to the common SDI system in this study, utilizing statistical analyses. The plant yields, amount of water consumption (L), productivity (g), water use efficiency (g/L), and fertilizer use efficiency (kg/g) varied widely between the two systems. The irrigation systems and programs affected plant growth, yield, and physiology [20]. The plant yields in the SDI and RDI were 1.46 and 2.87 kg/m$^2$, respectively, similar to a plant yield of 2.58 kg/m$^2$ when a substrate composed of coconut shell fiber was used [21]. Maximum hydroponically yield with a value of 5.11 kg/m$^2$ was documented [22]. However, the yield of lettuce is highly divergent, so this is the difference from the literature. Concerning water use efficiency, cultivation techniques in different regions reported that production of 1 kg lettuce require 1.6–93 L of water [23]. In contrast, in this study, the water use efficiency for the SDI and RDI systems reached 6.56 and 22.81 g/L, respectively. The water use efficiency for the RDI system is 3.47 times the SDI. The RDI systems can save 30%–50% of the water [17], similar to this study.

Regarding the contents of macronutrients in the harvested lettuce plants, the nutrition values are summarized in Table 12 for both systems. Nitrogen in the hydroponic systems ranges from 30 to 50 g/kg [23], while the obtained N by SDI and RDI of this study were lower; 20.94 and 20.37 g/kg, respectively. The P content in the SDI system (5.12 g/kg) is higher than in the RDI system (2.68 g/kg). Typically, the P content in the lettuce leaves is between 4 and 7 g/kg [24]. The K contents in this study were 3 and 3.3 g/kg for the SDI and the RDI, respectively. These values are consistent with the previous literature [25], where K in a hydroponic system ranged from 3.2 to 58.9 g/kg. The Ca contents in this study are compatible with those obtained previously [21,24].

The RDI system is a new technology, and almost no references except a manufacturer's website were found to cover this topic. However, the RDI system was proposed as a potential solution for input use efficiency in the Middle East and North Africa (MENA), but without any justification [26]. Also, the RDI system was recently examined in the United Arab Emirates as a smart irrigation solution to face drought problems [27].

## 5. Conclusion

Regarding the irrigation system preferences, RDI was compared to the common SDI system. The RDI system had several advantages over the SDI system, such as; lower water consumption, higher productivity, and higher water and fertilizer use efficiency. Accordingly, the efficiency of the RDI system should be checked over a basis of year-round cultivation to identify the efficiency of this system in different seasons. Also, the efficiency of the RDI system should be examined for different crops. As a result of this study, modern irrigation systems should be adopted to save water and face the water crisis in Palestine and other MENA regions.

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