Water and Nitrogen use Efficiency of Lettuce under Water Stressed Growing Conditions

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ABSTRACT

Lettuce as an important vegetable crop warrants special research and attention. Because of environmental and economic concerns, it is necessary to determine the most efficient application levels of irrigation water and nitrogen fertilizer to achieve the optimum yield in this crop. Two field experiments were conducted to test the effect of deficit irrigation and nitrogen fertilizer applications on agronomic growth characteristics of lettuce. Experimental treatments were arranged in split strip plots based on a completely randomized block design with three replications. The irrigation and nitrogen treatments were considered at four levels (0, 25, 50, and 100% of the currently recommended water and N fertilizer for lettuce production). Results showed that 50% of irrigation water and 25% of nitrogen ($IR_{50}N_{25}$) treatment currently recommended for lettuce production led to significantly higher water (4.4 Kg DM/m^3) and N (45 kg DM/kg N) use efficiencies for the fall experiment in 2017. The same results for water of 3.9 kg DM/m^3 and N of 73.1 kg DM/kg were achieved in the spring experiment 2018. The optimum lettuce biomass yield was obtained for $IR_{50}N_{25}$ treatment in both experiments.

Keywords: *Lettuce, water, Nitrogen, Efficiency, Biomass.*

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Highlights of this paper

- The highest yield of lettuce could be obtained by maximum inputs of water and nitrogen fertilizer; however, it involves loss of water and nitrogen leach outs.
- Lower irrigation water and nitrogen fertilizer inputs lead to lower lettuce yield which is not economically justifiable.
- Optimum and economically justifiable lettuce yield is obtained when irrigation water and nitrogen fertilizer applications are optimized to achieve the highest efficiencies in inputs.

1. INTRODUCTION

Lettuce (*Lactuca sativa* L. var. longifolia) warrants special research and attention in California because California dominates the U.S. lettuce production. In the United States, between 2013 and 2017, lettuce was cultivated on over 121,000 ha per year. In California alone, annual revenue from lettuce is more than 2 billion dollars, which makes it the most valuable fresh vegetable in the country [1]. Annual consumption of all types of lettuce in 2015 was 11.1 kg per person in the U.S. [2].

Efficient water use by irrigation systems is becoming increasingly important, especially in arid and semi-arid regions with limited water resources. Drought is considered the single most important abiotic stress that limits crop production including lettuce. Drought occurs when water supplies cannot meet demands, and that can happen due to a variety of reasons. A primary cause of the recent California drought has been lack of precipitation in recent years. This situation caused pressure on the ground water supplies in the state during the last decade. According to Chaichi, et al. [3] numerous physiological responses of plants to water deficit generally vary with the severity as well as the duration of the water stress.

The large quantity of nitrogen, which accumulates in the ecosystem through fertilizer use causes great concerns for health and environmental aspects. To the contrary, a limited amount of nitrogen adversely affects crop yield and yield components. Senyigit and Kaplan [4] recommended that there should be strict limits on the content of nitrogen in lettuce crops because of its potentially adverse effect on human health.

One of the nitrogen properties is mobilization when it interacts with water. Hence, the higher level of irrigation cannot guarantee the most availability of nitrogen for a vegetable such as lettuce. Thus, it is necessary to determine the most efficient levels of irrigation, and nutrients such as nitrogen to achieve the optimum yield Chaichi, et al. [5]. Awaad, et al. [6] showed that nitrogen and irrigation treatments caused higher chlorophyll and water content as well as dry matter in lettuce. Sabat, et al. [7] found that different levels of irrigation and nitrogen had a significant effect on lettuce yield and yield components. Soundy, et al. [8] reported that irrigation level of 75% with a nitrogen level of 50% caused the highest yield and water content in sunflower.

There has been considerable research about the interaction of different fertilizers and irrigation levels on various type of vegetables, not only in the United States but also in the other parts of the world. However, there has not been a lot of research about the interaction of nitrogen and irrigation levels on lettuce through efficient water and fertilizer use system. The goal of this research was to identify the most efficient levels of water and nitrogen fertilizer application to achieve an optimum and economically justifiable yield of lettuce.

2. MATERIALS AND METHODS

This research project was designed to study the interaction effect of irrigation systems and nitrogen fertilizer on lettuce (*Lactuca sativa* L. var. longifolia) growth and development. The experiment was conducted in the Spadra Research Farm of California State Polytechnic University, Pomona (Cal Poly Pomona) during the growing seasons of fall 2017 & spring 2018. The elevation of the experimental area is 242 m above the sea level. The coordination of the site is 34°3′ N, 117°45′ W. The experiment was conducted in a soil characterized as a sandy loam (66.7% sand, 25.5% silt and 7.8% clay) with pH =7.3, low level of organic matter (1.3gkg^{-1} and 23.7 and 14.5 mgkg^{-1} of available N and P, respectively).

The soil of the experimental site for both the experiments was tested for available nutrients. To determine the accurate amount of nitrogen fertilizer application, the water sample was also analyzed to determine the available level of nitrogen. The availability of nitrogen in water was very low and did not interfere with our experimental nitrogen treatments.

In the fall experiment 2017, after land preparation, the lettuce seedlings (*Lactuca sativa* L. var. longifolia) were transplanted into the experimental site on October 5th. The lettuce type was Roman with 65-70 days of the growing period. After transplanting, all the plots were irrigated in two rounds for two weeks to ensure the lettuce establishment. The actual irrigation treatments started on October 26th and continued to Dec 14th when the lettuce was ready for harvest. The same process was used for the experiment in spring 2018. After the land preparation on February 07th, the same lettuce type was transplanted to the field on February 15th.

A drip irrigation system (Valplastic USA Company) was employed for both the experiments. The tapes were laid out alongside the planting rows with 12 inches apart emitters with a flow rate of 0.27 gph at 8 psi (0.55 bar) pressure. Nitrogen fertilizer treatment levels were determined based on the soil lab test recommendation (45 Kg N/ha). Nitrogen fertilizer used in the research was a slow-release coated granule urea (GAL-Xe ONE) with 46% purity. The nitrogen fertilizer was applied to the plants, in bands of 3cm apart from the planting rows and 5cm deep in the soil, after the transplanting of seedlings were completed on October 23rd for the fall and on March 05th for the spring experiments, respectively.

The experimental treatments were arranged in a strip split plot based on a randomized complete block design with three replications. The main plots were assigned to four levels of nitrogen fertilizer consisting of a control (no fertilizer), 25, 50, and 100 percent of nitrogen currently recommended for maximum plant growth based on soil chemical analysis. The irrigation treatments consisting of four irrigation levels of control (0 percent), 25, 50, and 100 percent of required water to replenish weekly crop evapotranspiration were assigned to the sub plots within the main plots. Every single plot contained three rows of lettuce for which there was 90 cm buffer space between the rows and 25 cm buffer space between each plant on the rows.

Irrigation was scheduled based on a water balance, calculated as the sum of estimated daily crop evapotranspiration (ETc), subtracting the fraction of rainfall not exceeding the field capacity [9-11]. Actual crop water use requirements for lettuce was determined according to the crop evapotranspiration (ETc), estimated from the potential evapotranspiration (ETo), and using the crop coefficients (Kc) proposed using the following equation:

$$ETc = ETo \times Kc \qquad (1)$$

In Equation 1, ETo was obtained from CIMIS report, which uses a modifed Penman equation with a wind function. The parameter ETo was calculated by the Penman–Monteith method [12] using daily data of CIMIS recorded at the Cal Poly Pomona's weather station. The Kc is defined as the ratio of the crop evapotranspiration rate to the reference evapotranspiration rate. The localized step-wise Kc of Southern California was used in this study [12]. The water requirement for individual plots was measured for weekly irrigation. The amount of water applied base for each treatment was also calculated by using the following equation:

$$In = 0.623 \text{ x } A \text{ x } Kc \text{ x } ETo \;/\; IE \qquad (2)$$

Where in Equation 2, "In" is the volume of irrigation water (Gal), 0.623 the constant of the equation, A the plant canopy area (ft^2), Kc the crop coefficient, ETo the potential evapotranspiration (inch) and IE the irrigation efficiency.

The lettuce yield and yield components as well as biomass, water use efficiency, and nitrogen use efficiency were measured after 8 to 10 weeks of each experimental commencement. Other agronomic characteristics such as plant height and leaf number were measured on a weekly basis. The data were analyzed by SAS statistical program and means were compared by LSD (least significant difference) procedure, and the plots were created using the MS-Excel program.

3. RESULTS AND DISCUSIONS

3.1. Leaf Number per Plant

The leaf number per plant followed a significant increasing trend as the irrigation levels increased in the fall and spring experiments Table 1.

The highest leaf number (20 leaves) was observed in IR_{100} for both fall and spring experiments. The lowest leaf number in both fall and spring experiments belonged to IR_0 (average of 16.8 and 14.4 leaves per plant, respectively) Table 1. Sabat, et al. [7] demonstrated that higher levels of irrigation and nitrogen led to three times more leaf numbers compared to control (IR_0 and N_0) in lettuce. The higher leaf number per plant can be determined by more nodes on the crop shoot [13]. The higher number of leaves per plant in IR_{50} and IR_{100} could be explained by the higher nodes due to less water stress in these treatments.

Furthermore, none of the nitrogen levels resulted in any significant difference towards the leaf number characteristic in the fall experiment. In the spring experiment, the increasing trend in leaf number per plant did not follow any identical pattern Table 1. Sandra [14] reported that applying lower nitrogen levels at the termination of lettuce growing season did not show any significant effect in leaf numbers compared to higher nitrogen levels [15, 16]. Our results are supported by other researcher's findings on sunflower [17] corn [18] and lettuce [19].

3.2. Plant Height

In the fall experiment 2017, the plant height demonstrated an increasing trend as the irrigation and nitrogen levels increased. IR_{100} (24.08 cm) and N_{100} (21.77 cm) resulted in the highest plant heights compared to the other treatments Table 1.

In the spring 2018 experiment, increasing irrigation and nitrogen levels positively affected the plant height as IR_{100} (21.9 cm) and N_{100} (22.2 cm) treatments led to the highest plant height Table 1.

Nitrogen is a major component of the chlorophyll molecule, which is essential for plants growth. It is expected that higher nitrogen absorption in N_{100} by the plant could enhance chlorophyll production in lettuce. Thus, a higher amount of chlorophyll could lead to higher plant height. Stefanelli, et al. [10] showed that increasing nitrogen fertilizer from 30% to 100% positively affected lettuce height compared to control (N_0). Hoque, et al. [20] reported that applying nitrogen fertilizer in the form of Urea caused a higher chlorophyll content in lettuce compared to control. Our results for this agronomic characteristic is supported by other researchers' work [21].

The plant height followed an increasing trend during both growing seasons across all irrigation treatments. Significantly higher plant height at IR_{100} compared to other irrigation treatments was observed all through the growing seasons. It is assumed that the higher water content in the plants facilitates the movement of nutrients to the upper growing parts of the plant [22].

Table-1. Main effects of irrigation and nitrogen fertilizer on leaf number per plant and plant height of lettuce in fall 2017 and spring 2018 experiments.

Fall 2017			Spring 2018		
Treatments	Leaf number (Per Plant)	Plant height (cm)	Treatments	Leaf number (Per Plant)	Plant height (cm)
Ir_0	16.83 cb	16.45 c	Ir_0	14.40 c	16.00 c
Ir_{25}	16.68 c	17.69 c	Ir_{25}	17.60 b	20.10 b
Ir_{50}	17.82 b	19.55 b	Ir_{50}	19.50 a	21.80 a
Ir_{100}	20.30 a	24.08 a	Ir_{100}	20.50 a	21.90 a
N_0	16.42 a	17.37 c	N_0	15.70 c	16.60 d
N_{25}	19.00 a	18.59 c	N_{25}	19.50 a	19.90 c
N_{50}	18.12 a	20.05 b	N_{50}	18.20 b	21.00 b
N_{100}	18.09 a	21.77 a	N_{100}	18.50 ab	22.20 a

* The means in each column with the same letter are not statistically different ($p \leq 0.05$).

3.3. Plant Biomass

Lettuce biomass followed a significant increasing trend as irrigation and nitrogen levels increased in both fall 2017 and spring 2018 experiments. The highest lettuce biomass was obtained in $IR_{100}N_{100}$ and the least in IR_0N_0 treatments in both growing seasons Figure 1 and 2.

In spring experiment 2018, except for IR_{100} irrigation level, increasing the nitogen application at other irrigation levels did not significantly increase the biomass production in lettuce Figure 2. These results indicated that water availability played a more significant role in lettuce production compared to nitrogen [23].

The higher concentration of nitrogen in control (irrigation 0%) treatment could cause a higher water potential in lettuce, which led to lower biomass production Figure 2. It seems that the highest irrigation level could provide more nitrogen along with lower water potential to produce higher biomass. For IR_{100} treatment, the highest biomass was produced for N_{50} and N_{100} treatments, even though there was not a significant difference between them. Despite a significantly lower biomass production in $IR_{50}N_{25}$ treatment compared to previous treatments, it seems that the latter treatment is most efficient choice considering efficiency in water and nitrogen fertilizer use as well as economic yield justifications Figure 2. It is assumed that higher water and nitrogen levels provided optimum conditions for the leaves to produce more chlorophyll content, and subsequently, more protein to support lettuce growth to achieve higher biomass. Tourbatinejad, et al. [21] reported that higher water and nitrogen treatments up to 100% compared to the control (0%) caused a higher protein content and total biomass in corn. Robin, et al. [24] demonstrated that applying N_{100} caused a higher yield and yield components in corn [4, 14].

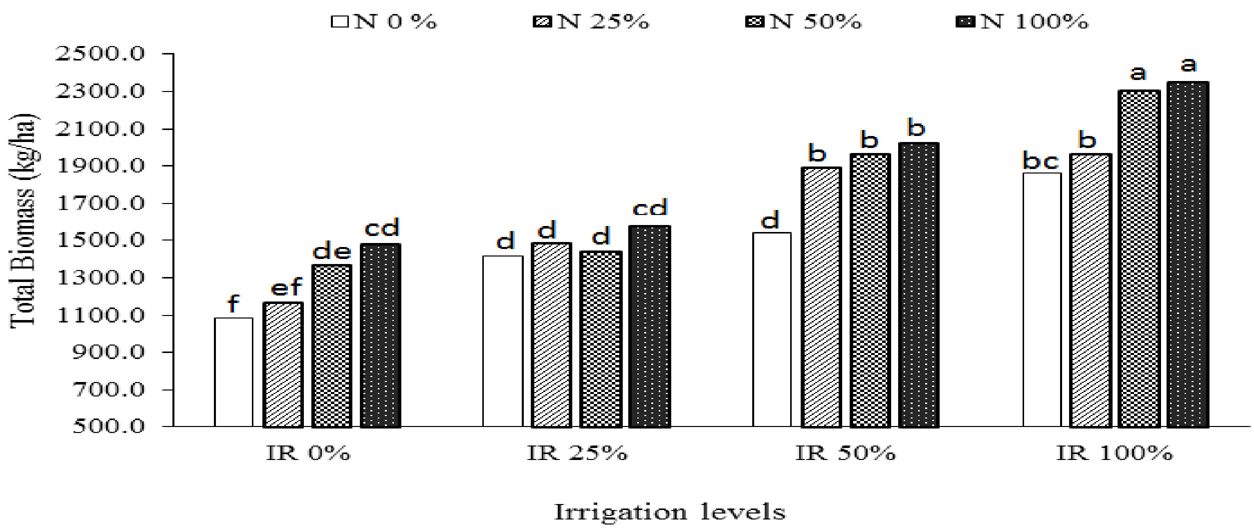

Figure-1. Interaction effect of irrigation and nitrogen treatments on lettuce biomass (dry matter) yield, fall experiment 2017.
No significant difference ($p \leq 0.05$).

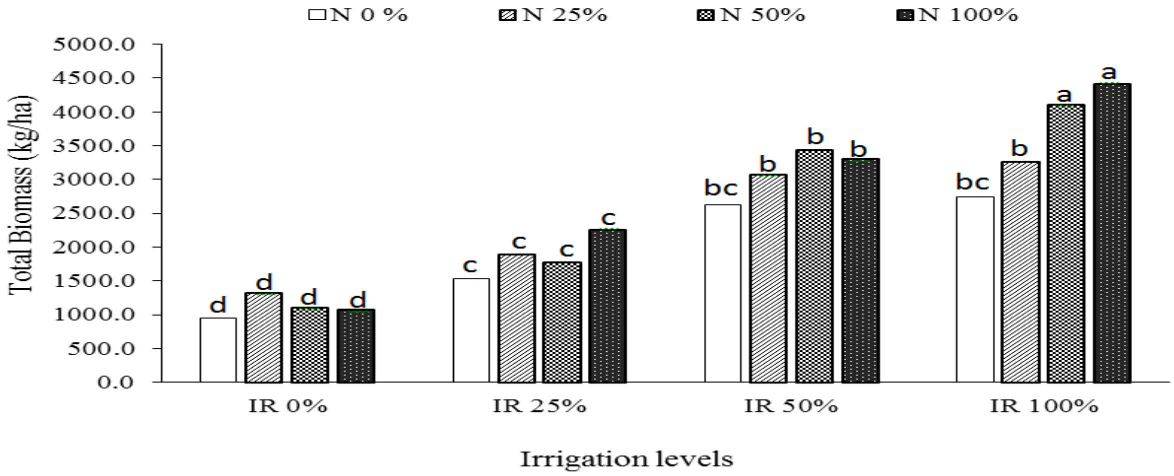

Figure-2. Interaction effect of irrigation and nitrogen treatments on lettuce biomass (dry matter), spring experiment 2018.
No significant difference ($p \leq 0.05$) between treatments with the same letters.

3.4. Nitrogen Use Efficiency

Our results demonstrated that water and nitrogen use efficiency for IR_{50} treatment was higher compared to IR_{100} treatment. This result supports lettuce production in water deficit conditions such as those prevailing in California farming regions.

Understanding the significance of nitrogen use efficiency is important because it not only helps economically but also helps lower environmental impact. Nitrogen use efficiency was significantly higher at N_{25} level compared to other nitrogen levels in the fall growing season Figure 3. During the fall experiment, increasing nitrogen fertilizer in each irrigation level ended up to decreasing the nitrogen use efficiency in lettuce Figure 3. The lowest nitrogen use efficiency (8.8 kg DM/kg N) occurred in $IR_0N_{100\ \%}$ treatment levels, while the highest efficiency of nitrogen use (46.8 kg DM/kg N) was observed in IR_{50} and IR_{100} treatment levels receiving N_{25} treatment Figure 3. From the environmental and economical point of views, it seems that the best nitrogen use efficiency was achived in $IR_{50}N_{25}$ treatment level. The same trend of nitrogen use efficiency as the fall experiment was observed in the spring experiment. Nitrogen use efficiency followed an increasing trend as irrigation levels increased Figure 3 and 4. However, increasing levels of nitrogen in each irrigation level demonstrated a decreasing trend in nitrogen use efficiency. This agrees with the findings by Francesco [25] who had reported that the lowest nitrogen use efficiency was recorded in the highest nitrogen fertilizer level in lettuce [14].

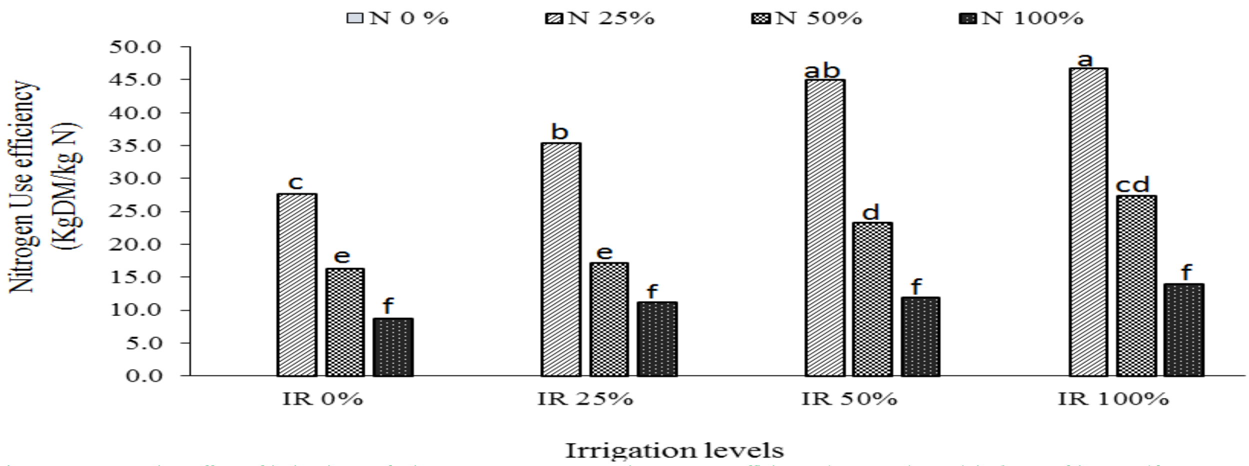

Figure-3. Interaction effect of irrigation and nitrogen treatments on nitrogen use efficiency (Kg DM/Kg N) in lettuce biomass (dry matter) yield, fall experiment 2017.
No significant difference ($p \leq 0.05$) between treatments with the same letters.

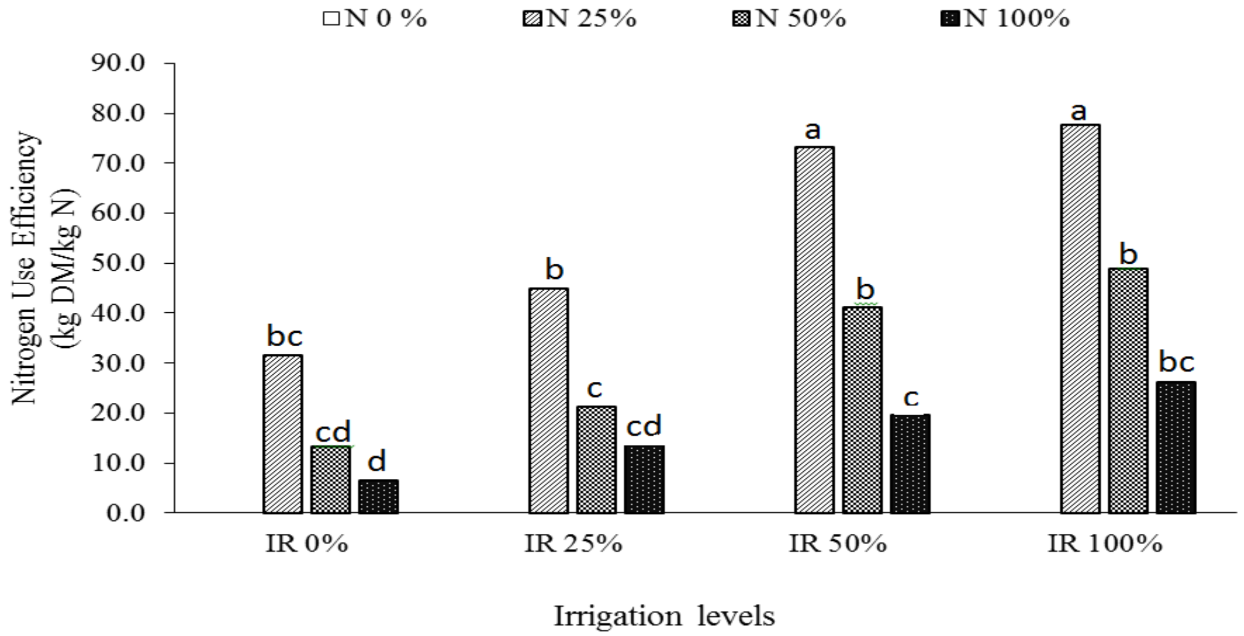

Figure-4. Interaction effect of irrigation and nitrogen treatments on nitrogen use efficiency (kg DM/kg N) in lettuce biomass (dry matter) yield, spring experiment 2018.
No significant difference ($p \leq 0.05$) between treatments with the same letters.

3.5. Water Use Efficiency

By increasing the irrigation levels, a decreasing trend in water use efficiency was observed both in the fall and spring experiments Figure 5 and 6. The most efficient water use of 8.8 kg DM/m^3 was observed in $IR_{25}N_{100}$ treatment. The least water use efficiency of 2.2 and 2.3 kg DM/m^3 were recorded in $IR_{100}N_0$ and as well as $IR_{100}N_{25}$ treatments, respectively Figure 5 and 6.

It seems that IR_{50} treatment could provide enough irrigation water for lettuce to achieve the optimum yield and yield components compared to other irrigation treatments. Sefer [13] showed that water use efficiency was significantly increased as water levels decreased to 45% in lettuce. Andriolo, et al. [22] also reported that IR_{50} caused a higher water use efficiency in lettuce compared to the other corresponding treatments. These findings agree with our results.

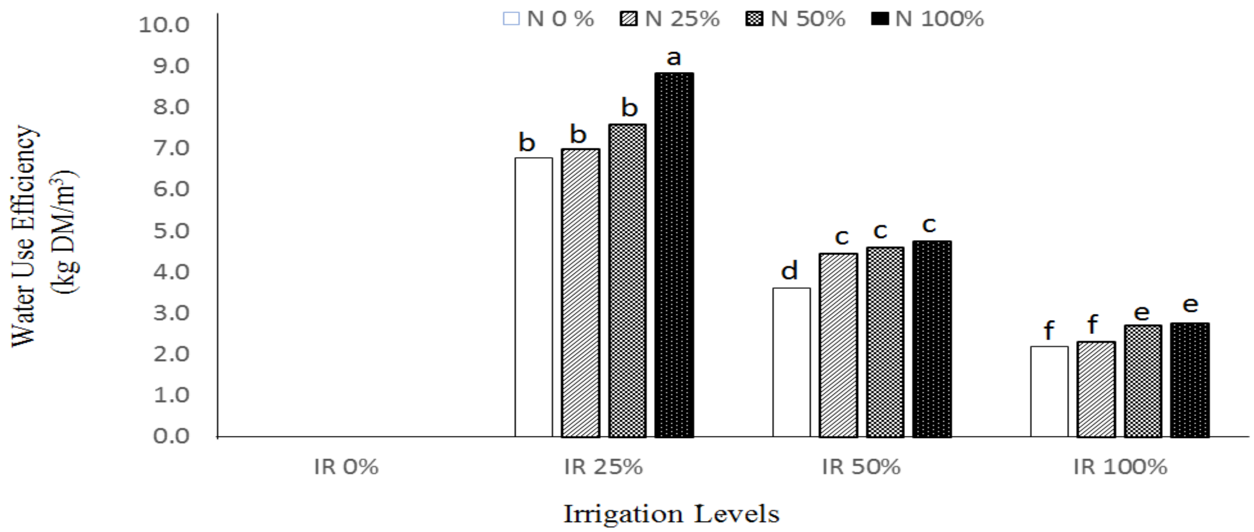

Figure-5. Interaction effect of irrigation and nitrogen treatments on water use efficiency (kg DM/m^3) in lettuce biomass (dry matter) yield, fall experiment 2017.
No significant difference ($p \leq 0.05$) between treatments with the same letters.

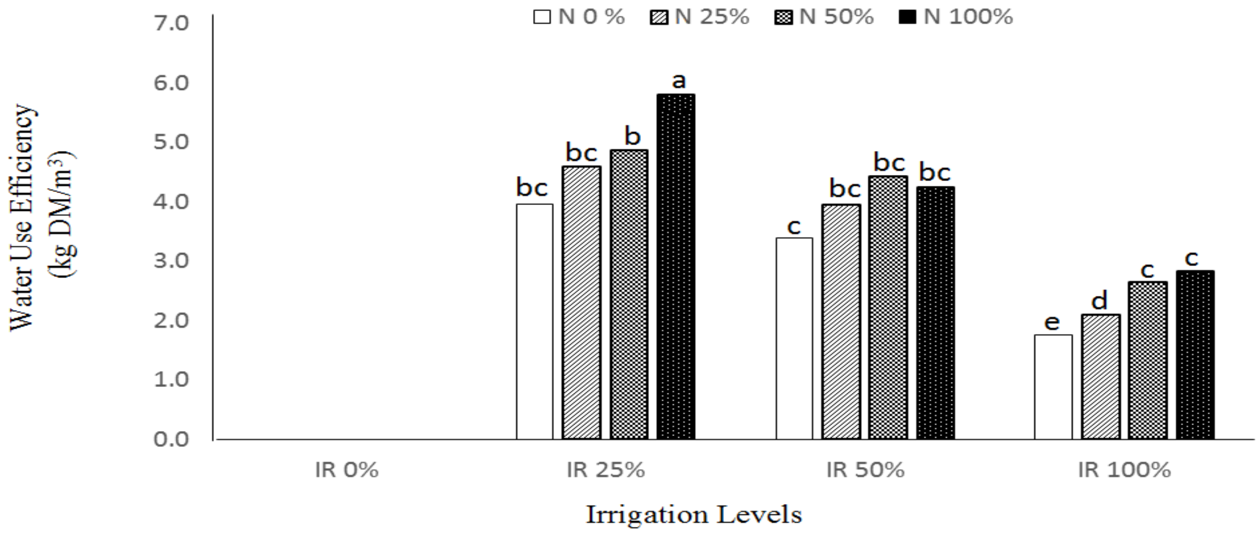

Figure-6. Interaction effect of irrigation and nitrogen treatments on water use efficiency (kg DM/m³) in lettuce biomass (dry matter) yield, spring experiment 2018.
No significant difference (p≤0.05) between treatments with the same letters.

4. CONCLUSIONS

Different irrigation and nitrogen treatments significantly affected lettuce yield and yield components in both fall and spring experiments. It was found that higher irrigation and nitrogen levels produced the highest lettuce yield. However, the most efficient water and nitrogen fertilizer use in lettuce was recorded at $IR_{50}N_{25}$ treatment in both the growing seasons. Since the most important agricultural concern in California and elsewhere in the world is to achieve the best water and nitrogen use efficiency, $IR_{50}N_{25}$ treatment could be recommended for lettuce production under the environmental conditions of this experiment. This is not only because of water and nitrogen saving but more preferably, because of more environmentally friendly practice with economically justifiable yield.

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