Greenhouse Plant Production Journal 3(3) (2026).60–76 gppj.araku.ac.ir

Greenhouse Plant Production Journal

Spatial Variability of Greenhouse Crop Water Requirements in Alborz Province, Iran: A Comparison of the Almeria and Solar Radiation Methods

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Original Article

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Citation: Sepehri Sadeghian, S. and Zarei, Gh. 2026. Spatial Variability of Greenhouse Crop Water Requirements in Alborz Province, Iran: A Comparison of the Almeria and Solar Radiation Methods. Greenhouse Plant Production Journal 3(3): 60-76.

https://doi.org/10.66224/gppj.3.3.60

KEYWORDS

Evapotranspiration
Spatial variability
Radiation-based methods
Net water requirement
Greenhouse crops

ABSTRACT

Greenhouse cultivation is recognized as an effective strategy for enhancing water productivity; however, its success depends on model-based estimation of crop water requirements under regional climatic conditions. To date, no comprehensive study has been conducted on water requirements of greenhouse crops in Alborz Province. This study estimated net water requirements for ten major greenhouse crops in Alborz Province (solanaceous crops, leafy vegetables, and strawberry) using long-term meteorological data from nine weather stations. Reference evapotranspiration was calculated using the Almeria radiation (AR) and solar radiation (SR) methods, with crop coefficients applied to determine net requirements. Spatial patterns and method agreement were evaluated using boxplots, heatmaps, and regression. The results indicated that annual water requirements ranged from 833.8 to 1,189.7 mm, with bell pepper exhibiting the highest and cucumber the lowest requirements. Among solanaceous crops, bell pepper and eggplant showed the highest values and cucumber the lowest, while among leafy vegetables, cabbage exhibited the highest requirement and basil the lowest. A clear spatial gradient was observed, with Eshtehard, Nazarabad, and Meshkin Dasht showing the highest requirements, and Asara, Taleqan, Payam Airport, and Zidasht the lowest. The AR method consistently produced higher estimates than SR, while both methods showed similar spatial patterns and strong correlation. This study provides the first comprehensive database of estimated water requirements for major greenhouse crops in Alborz Province, serving as a preliminary reference for irrigation planning, water allocation, greenhouse licensing, and sustainable development in the region.

ARTICLE HISTORY

Received: 20 July 2026
Revised: 20 August 2026
Accepted: 27 August 2026

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Publisher: Arak University

1. Introduction

Iran is confronting an unprecedented water crisis, characterized by extreme water stress (agricultural water stress index of 0.94) and a declining trend in terrestrial water storage driven primarily by anthropogenic groundwater extraction for the agricultural sector (Dehghanpir *et al*., 2024; Yuan *et al*., 2025). The agricultural sector accounts for 70–90% of the country's renewable water consumption, with low irrigation efficiency contributing to widespread groundwater depletion and a situation described as "water bankruptcy" (Nouri *et al*., 2023; Ashraf *et al*., 2023). Under such circumstances, any technical or managerial strategy capable of enhancing water productivity is of strategic importance. Greenhouse cultivation has emerged as one of the most effective solutions in this regard. In the controlled environment of a greenhouse, through the management of environmental factors such as temperature, humidity, and radiation, evapotranspiration rates are significantly reduced, and water productivity increases by 5 to 10 times compared to open-field conditions (Rezaverdinejad *et al*., 2017; Baudoin *et al*., 2017; Eshghi *et al*., 2026). Studies conducted in hyper-arid regions have demonstrated that greenhouse cultivation can achieve significantly higher crop water-use efficiency and substantially greater yields compared to open-field production. In the United Arab Emirates, for example, Al Tamimi *et al*. (2022) reported that water use efficiency in a cooled greenhouse was approximately three times higher than in open fields or shade houses, with substantially greater crop yields under greenhouse conditions. Consequently, agricultural policymakers in Iran have prioritized greenhouse development within their five-year national plans, and the cultivated area under greenhouse production has experienced remarkable growth in recent years, expanding from approximately 588 hectares in 1996 to over 18,000 hectares by 2021 (Moradi *et al*., 2026). Nevertheless, the sustainable development of greenhouses cannot be achieved without precise planning grounded in local knowledge. One of the most critical prerequisites for such planning is the accurate estimation of crop water requirements tailored to the climatic conditions of each region. In Alborz Province, for instance, the issuance of greenhouse establishment and operation permits is contingent upon securing a reliable water right, which further underscores the urgent need for access to reliable estimated water requirement data.

At the international level, extensive research has been conducted on estimating the water requirements of greenhouse crops using various methodologies. The reference standard for estimating reference evapotranspiration (ETo) is the FAO-56 Penman-Monteith method, introduced by Allen *et al*. (1998). However, the direct application of this method under greenhouse conditions presents limitations, as climatic parameters inside greenhouses differ considerably from those in open fields (Fernández *et al*., 2010). Previous research has demonstrated that conventional evapotranspiration estimation methods, including Turc, Jensen-Haise, Hargreaves-Samani, and Blaney-Criddle, exhibit limited accuracy under greenhouse conditions due to the distinct microclimate and radiative environment compared to open-field settings (Nikolaou *et al*., 2019). In contrast, approaches adapted to controlled environments, such as the Penman-Monteith and Stanghellini models, provide more reliable estimates (Nikolaou *et al*., 2019; Katsoulas & Stanghellini, 2019). Among simplified radiation-based alternatives, the Almeria radiation method (Bonachela *et al*., 2006) and the solar radiation method (Baille, 1996) have been shown to offer acceptable accuracy with limited data requirements, making them practical for greenhouse applications (Fernández *et al*., 2010, 2009). Furthermore, a critical modification has been made to the application of the FAO-Penman-Monteith method in greenhouses, wherein the aerodynamic resistance (ra) value has been corrected from the standard 150 s m^{-1} to 295 s m^{-1} to improve the agreement between ETo estimates and measured data inside greenhouses (Fernández *et al*., 2010). Recent methodological developments have addressed the challenge of estimating reference evapotranspiration (ET_o) in greenhouse environments where comprehensive meteorological data are often unavailable. Gaafer *et al*., (2024) demonstrated that ET_o can be reliably estimated in fan-and-pad greenhouses using limited climatic inputs—specifically air temperature, wind speed, and site-specific parameters including altitude, latitude, and sunshine hours—with results showing good statistical agreement with both Class-A pan evaporation measurements and Penman-Monteith estimates derived from full indoor climate datasets. This approach holds particular value for regions facing meteorological data scarcity and underscores the critical importance of air temperature as the most fundamental parameter for ET_o estimation in protected cultivation systems (Gaafer & Mohammed, 2024).

A complementary study by Gaafer and Mohammed (2024) further validated a simplified procedure combining heat transfer modeling for internal temperature prediction with the FAO-56 Penman-Monteith method, confirming that reliable ETo estimates can be obtained without direct measurement of all standard meteorological variables. In parallel with these simplified physical approaches, researchers have increasingly turned to machine learning algorithms to enhance evapotranspiration prediction accuracy in greenhouse environments. Recent studies have shown that tree-based algorithms including Random Forest, XGBoost, and Gradient Boosting achieve R^2 values exceeding 0.90 for crop evapotranspiration prediction in greenhouse settings (Khoshsimaie Chenar *et al*., 2025), with appropriate spatial sampling of atmospheric conditions—even utilizing only 10% of available data—yielding acceptable results (Averbuch & Moshelion, 2024). These advances reflect a broader trajectory toward precision agriculture and the integration of artificial intelligence in irrigation decision-support systems. Recent advances in artificial intelligence have enabled real-time, species-specific optimization of greenhouse environments (Bayat & Bayat, 2025). Recent frameworks emphasize dynamic, plant-centered greenhouse climate control based on real-time physiological indicators (Shojaei-Nia *et al*., 2026). Regarding crop coefficient determination for greenhouse crops, lysimeter-based studies have revealed that coefficients under protected cultivation are considerably higher than those reported for open-field conditions due to modifications in canopy structure and plant architecture. Baştuğ *et al*. (2024) conducted drainage lysimeter experiments in Antalya, Turkey, under Mediterranean plastic greenhouse conditions, reporting mid-season crop coefficients (K_c mid) ranging from 1.4 to 1.8 for spring cultivation and 1.6 to 1.9 for autumn cultivation across tomato, eggplant, pepper, and cucumber. This variability in crop coefficients underscores the necessity of establishing region- and system-specific coefficients rather than relying on generalized values derived from open-field studies.

Within the national context, several studies have been conducted across various regions of Iran to estimate crop coefficients and water requirements for greenhouse crops, employing a range of methodological approaches including lysimetry, drainage lysimeters, water balance, volumetric balance, and field experiments (Table 1). The reported crop coefficient values exhibit considerable variation across crops and locations, reflecting the influence of climatic conditions, greenhouse management practices, and methodological differences on crop water requirements. For tuberose in Varamin, Delavar *et al*. (2015) reported K_c values ranging from 0.5 to 0.7 with a total water requirement of 350 mm. In Urmia, Rezaverdinejad *et al*. (2017) determined crop coefficients between 0.19 and 1.29 for cucumber and tomato using lysimetry, while Ebrahimi *et al*. (2018) reported K_c values of 0.14–0.93 for basil across different growth stages. Rahimi-Khoob *et al*. (2019) in Karaj employed a water balance approach and reported basil Kc values of 0.30–0.86. For rose cultivars under hydroponic greenhouse conditions in Arak, Keykhaei *et al*. (2020) reported K_c values ranging from 0.70 to 0.96 with annual evapotranspiration of 1,313–1,480 mm. In Hamedan, Rezvani *et al*. (2022) combined soil water balance and Penman-Monteith methods to determine cucumber K_c values of 0.63–1.43 across different seasons. Nikbakht *et al*. (2022) reported a relatively high crop coefficient of 0.99 for sedum under greenhouse conditions using volumetric balance. Across multiple climatic zones including Pakdasht, Isfahan, Jiroft, and Hamedan, Zarei *et al*. (2018) reported cucumber K_c values ranging from 0.51 to 1.70. The diversity of methods and the variability in reported values underscore the necessity of conducting location-specific studies to generate reliable water requirement estimation for greenhouse crops, particularly in climatically diverse regions such as Alborz Province.

Table 1. Summary of previous studies on greenhouse crop water requirements in Iran.

Researchers (Year)	Location	Crop(s)	Method	Crop Coefficient (Kc)
Delavar *et al*. (2015)	Varamin	Tuberose	Lysimetry	0.5–0.7
Rezaverdinejad *et al*. (2017)	Urmia	Cucumber, Tomato	Lysimetry	0.19–1.29
Ebrahimi *et al*. (2018)	Urmia	Basil	Lysimetry	0.14- 0.93
Rahimi-Khoob *et al*. (2019)	Karaj	Basil	Water balance	0.30–0.86
Keykhaei *et al*. (2020)	Arak	Rose cultivars	Drainage lysimeter	0.70–0.96
Rezvani *et al*. (2022)	Hamedan	Cucumber	Soil water balance + Penman-Monteith	0.63–1.43
Nikbakht *et al*. (2022)	Urmia	Sedum	Volumetric balance	0.99
Zarei *et al*. (2018)	Pakdasht, Isfahan, Jiroft, Hamedan	Cucumber	Field experiment	0.51–1.70

The review of previous studies reveals several critical gaps. First, most national research has focused on limited crop types, primarily cucumber and tomato, while neglecting other important greenhouse crops including leafy vegetables, strawberry, and other solanaceous crops such as eggplant and peppers. Second, although Alborz Province is recognized as one of Iran's major greenhouse production hubs with approximately 446 hectares under cultivation (Alborz Province Agricultural Jihad Organization, 2023) and a planned expansion to 2,000 hectares, no comprehensive study has been conducted on the water requirements of its major greenhouse crops. Despite a few scattered case studies on specific greenhouse crops in the province, no comprehensive research has simultaneously covered all major greenhouse crops, including solanaceous crops, leafy vegetables, and strawberry, across the diverse climatic zones of Alborz Province. This is particularly critical given the province's climatic diversity, ranging from the warm, arid conditions of Eshtehard to the cold, high-altitude conditions of Taleqan, which makes water requirement estimation more complex yet more essential. Third, despite the recognized influence of method selection on the accuracy of evapotranspiration estimates and subsequent irrigation decisions, few studies have systematically compared different ETo estimation approaches under identical greenhouse conditions. Foliar application of salicylic acid has been shown to enhance growth and yield in greenhouse eggplant (Arvin *et al*., 2026). The applicability of a given method is highly dependent on greenhouse type, climate control capabilities, and data availability, as different models have been developed for distinct purposes—ranging from simple irrigation scheduling to detailed climate simulation (Katsoulas and Stanghellini, 2019).

A comprehensive review by Katsoulas and Stanghellini (2019) emphasized that models developed for different applications cannot always be directly compared, as they incorporate varying levels of detail regarding stomatal and aerodynamic conductance, and their sensitivity to parameters differs across greenhouse types (e.g., low versus high technology, closed versus highly ventilated structures, covering films, etc.). This suggests that method selection should be guided by the specific objectives of the irrigation plan, the technological level of the greenhouse, and the available meteorological data, rather than relying on a one-size-fits-all approach. Fourth, given the national policies for greenhouse development and the requirement to provide water rights for operation permits, access to localized and model-based water requirement estimates is not only a scientific necessity but also an administrative imperative for decision-makers and agricultural policymakers involved in greenhouse licensing and water resource allocation.

To address these gaps, this study was designed to estimate the net water requirement of major greenhouse crops in Alborz Province, including ten crop species across three distinct groups: solanaceous crops (tomato, cucumber, eggplant, bell pepper, and chili pepper), leafy vegetables (lettuce, cabbage, basil, and mint), and greenhouse fruit crops (strawberry). Using long-term meteorological data from nine weather stations across the province, reference evapotranspiration inside greenhouses was calculated using both the Almeria radiation method and the solar radiation method. Crop coefficients derived from authoritative international sources were then applied to estimate the net water requirement for each crop based on its typical growing period in the region. This study offers two key innovations. First, it represents the first comprehensive investigation in Alborz Province to simultaneously estimate the water requirements of a wide range of greenhouse crops using two complementary methods, with results disaggregated at the county level to reflect the province's climatic diversity. Second, by establishing a practical database of crop water requirements, it provides a scientific foundation for agricultural policymakers and decision-makers to support greenhouse development planning, water resource allocation, and cropping pattern prioritization in Alborz Province. This spatially disaggregated information enables evidence-based strategies for sustainable greenhouse expansion, ensuring that development aligns with the actual water needs of different crops across the province's diverse climatic zones, thereby contributing to improved water productivity and regional food security.

2. Materials and Methods

2.1. Study Area and Climatic Data

Alborz Province, with an area of approximately 5,122 km², is located in north-central Iran, between latitudes 35°30′ to 36°15′ N and longitudes 49°30′ to 51°15′ E. The province is bordered by Mazandaran to the north, Markazi Province to the south, Tehran Province to the east, and Qazvin Province to the west. The province exhibits considerable climatic diversity, with northern counties (Taleqan and Asara, elevation > 1,800 m) characterized by cold, mountainous climates, and southern and eastern counties (Eshtehard, Nazarabad, and Meshkin Dasht, elevation < 1,300 m) characterized by warm, semi-arid climates. In this study, long-term meteorological data were obtained from nine weather stations across Alborz Province.

The data were sourced from the Iran Meteorological Organization (IRIMO) and covered the period from the establishment of each station to the end of 2024, with a daily temporal resolution. To ensure consistency in spatial analysis, the overlapping period with complete records across all stations was used. Quality control procedures included outlier detection and removal, as well as linear interpolation to fill missing data (less than 5% of the total dataset). Stations were selected based on the availability of reliable long-term records representing the diverse climatic zones of the province. Station specifications are presented in Table 2, and their spatial distribution across the province is shown in Figure 1.

2.2. Identification of Major Greenhouse Crops

Major greenhouse crops cultivated in Alborz Province were identified through three complementary approaches: (i) a review of official reports published by the Alborz Province Agricultural Jihad Organization, (ii) field visits to commercial greenhouse production units located throughout the province, and (iii) consultations with greenhouse production specialists and agricultural extension experts.

Based on these investigations, ten economically important greenhouse crops were selected for this study, including tomato (*Solanum lycopersicum* L.), cucumber (*Cucumis sativus* L.), eggplant (*Solanum melongena* L.), chili pepper (*Capsicum annuum* L.), bell pepper (*Capsicum annuum* var. *grossum*), strawberry (*Fragaria* × *ananassa* Duch.), lettuce (*Lactuca sativa* L.), cabbage (*Brassica oleracea* var. *capitata*), basil (*Ocimum basilicum* L.), and mint (*Mentha* spp.) (Sepehri *et al*., 2026). These crops represent the dominant greenhouse vegetable, leafy vegetable, and fruit crops cultivated in Alborz Province. The cultivated areas for each group are presented in Tables 3 and 4. Field surveys indicated that the predominant greenhouse covering material in the province is single-layer polyethylene film with a thickness of 4-6 mil. The light transmission characteristics of these covers are presented in Table 5. Based on these characteristics and field observations, a cover transmission coefficient (τ) of 0.8 was selected for all calculations.

Table 2. Specifications of weather stations used in this study.

No.	Station	County	Longitude (E)	Latitude (N)	Elevation (m)	Mean Annual Precipitation (mm)	Mean Annual Temperature (°C)
1	Eshtehard	Eshtehard	50°22′17″	35°43′12″	1191	357.8	15.2
2	Meshkin Dasht	Fardis	50°57′21″	35°45′30″	1289	306.6	14.6
3	Payam Airport	Chaharbagh	50°55′00″	35°47′00″	1184	256.5	12.3
4	Karaj	Karaj	50°56′16″	35°46′49″	1293	297.8	14.7
5	Asara	Karaj	51°11′08″	36°02′26″	1864	342.7	10.4
6	Hashtgerd	Savojbolagh	50°45′13″	36°00′48″	1613	218.9	14.0
7	Nazarabad	Nazarabad	50°33′30″	35°56′50″	1168	273.5	15.2
8	Taleqan	Taleqan	50°46′11″	36°10′49″	1897	429.3	9.4
9	Zidasht	Taleqan	50°40′33″	36°07′39″	2255	339.6	11.3

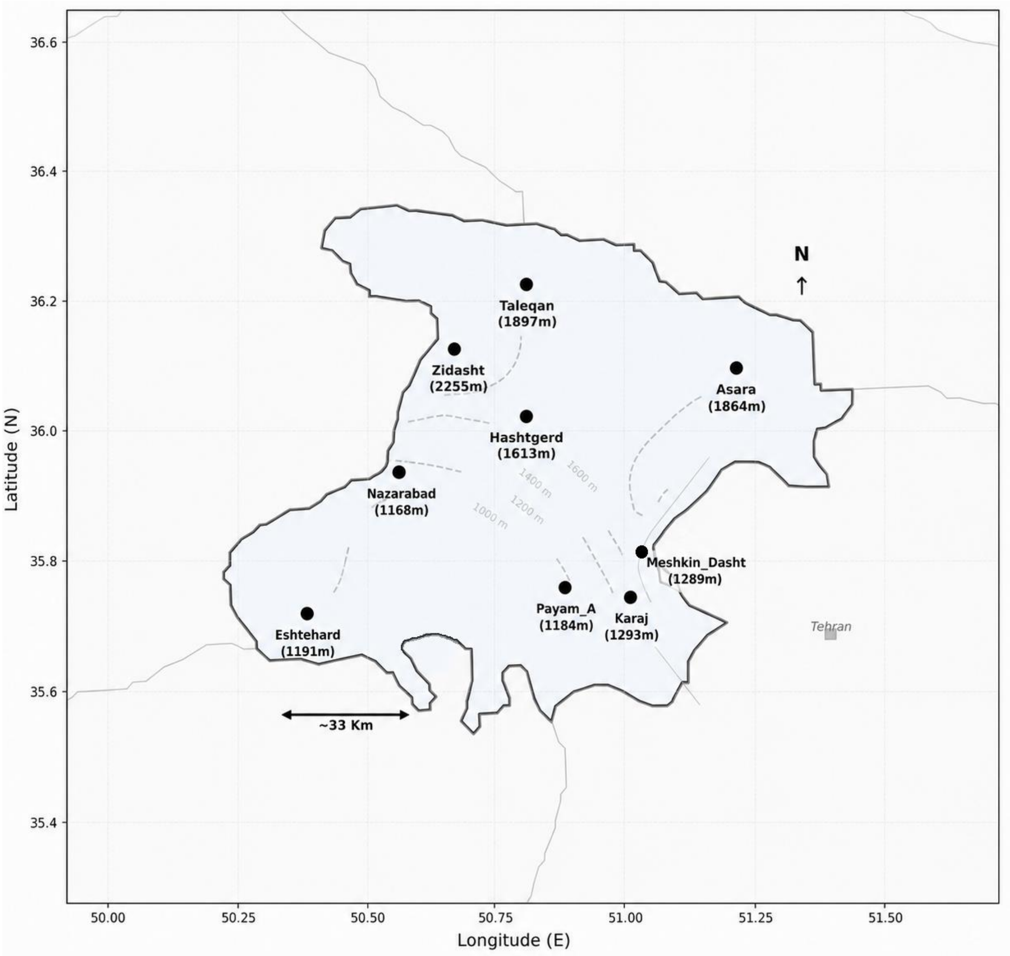

Figure 1. Location map of the study area (Alborz Province, Iran) and the nine meteorological stations used in this study.

Table 3. Cultivated area of greenhouse solanaceous and leafy vegetable crops in Alborz Province (ha).

Crop	Cucumber	Tomato	Peppers (all types)	Eggplant	Leafy Vegetables	Total
Area	48.85	92.09	26.81	0.71	43.51	212.00

Table 4. Cultivated area of strawberry, medicinal plants, and ornamental plants in Alborz Province (ha).

Crop	Strawberry	Medicinal Plants	Ornamental Plants
Area	70.99	1.78	117.09

Table 5. Light transmission characteristics of polyethylene greenhouse covers (Azadsharaki *et al*., 2021; Maraveas *et al*., 2023; Cemek & Demir, 2005)

Cover Type	Thickness (mil)	Layers	Visible Light Transmission (%, PAR)	Long-wavelength IR Transmission (%)
UV-stabilized PE	4-6	Single	87-91	80
UV-stabilized PE	4-6	Double	75-80	63
IR-absorbing PE	4-6	Single	80-82	25-30
IR-absorbing PE	4-6	Double	65-68	-
Anti-drip PE	8	Single	90	35-40
Three-layer PE	-	-	85	-

2.3. Determination of Crop Growing Periods

The growing period (from planting to harvest) for each crop was determined based on expert consultations, field observations, and alignment with the greenhouse cropping calendar in the province. For crops with multiple cultivation cycles per year (i.e., leafy vegetables with short growing periods), the number of annual cultivation cycles was specified. A summary of growing period information is provided in Table 6.

2.4. Calculation of Reference Evapotranspiration Inside Greenhouses and Net Water Requirement

Given that the microclimate inside greenhouses differs considerably from outdoor conditions, reference evapotranspiration was estimated directly for greenhouse conditions. For this purpose, two complementary methods were employed, both based on outdoor climatic data adjusted for greenhouse cover characteristics. These methods were selected for their simplicity, limited data requirements, and validation in previous studies (Fernández *et al*., 2010; Bonachela *et al*., 2006; Baille, 1996).

Table 6. Growing period length, planting and harvest dates, and number of annual cultivation cycles for selected crops.

Group	Crop	Planting Date	Harvest Date	Number of Cycles per Year
Solanaceous Crops	Tomato	Early April	Late November	1
Solanaceous Crops	Cucumber	Early April	Late August	1
Solanaceous Crops	Eggplant	Early February	Late November	1
Solanaceous Crops	Chili Pepper	Early February	Late November	1
Solanaceous Crops	Bell Pepper	Early February	Late November	1
Leafy Vegetables	Lettuce, Cabbage	Year-round (4 cycles)	90 days after planting	4
Leafy Vegetables	Basil, Mint	Year-round (8 cycles)	45 days after planting	8
Greenhouse Fruit Crops	Strawberry	Early February	Late January	1

a) Almeria Radiation Method

This method, developed by Bonachela *et al*. (2006), estimates ET_o inside greenhouses based on outdoor solar radiation and greenhouse cover transmissivity. The main advantage of this method is its consideration of greenhouse physical characteristics, including structure, covering materials, and operational management (e.g., shading screens) (Fernández *et al*., 2010). Equations (1) and (2) represent this method:

$$ET_{oGH} = (0.288 + 0.0019 \times JD) \times R_o \times \tau (\text{for JD} \leq 220) \quad (1)$$

$$ET_{oGH} = (1.339 - 0.00288 \times JD) \times R_o \times \tau (\text{for JD} > 220) \quad (2)$$

where:

- ET_{oGH}: reference evapotranspiration inside the greenhouse (mm day^{-1})
- JD: Julian day
- R_o: daily solar radiation outside the greenhouse (mm day^{-1})
- τ: solar radiation transmissivity of the greenhouse cover (transmission coefficient)

b) Solar Radiation Method

This method, proposed by Baille (1996), is based on outdoor solar radiation, which is adjusted using the cover transmission coefficient and an empirical coefficient to estimate ET_o inside greenhouses. Equation (3) represents this method:

$$ET_{oGH} = \frac{K \times t \times RG_o}{2.5} \quad (3)$$

where:

- K: empirical coefficient ranging from 0.6 to 0.7 (adopted as 0.65 in this study)
- t: greenhouse cover transmission coefficient (0.8)
- RG_o: outdoor solar radiation (MJ m^{-2} day^{-1})

Table 7. Crop coefficients (K_c) used for estimation of net water requirements

Crop	Growth Stage	K_c Value	Source
Tomato	Initial	0.45	Baştuğ *et al*. (2024)
	Mid-season	1.90	Baştuğ *et al*. (2024)
	End	1.10	Baştuğ *et al*. (2024)
Cucumber	Initial	0.50	Baştuğ *et al*. (2024)
	Mid-season	1.80	Baştuğ *et al*. (2024)
	End	1.30	Baştuğ *et al*. (2024)
Eggplant	Initial	0.50	Baştuğ *et al*. (2024)
	Mid-season	1.70	Baştuğ *et al*. (2024)
	End	1.20	Baştuğ *et al*. (2024)
Bell Pepper	Initial	0.50	Baştuğ *et al*. (2024)
	Mid-season	1.70	Baştuğ *et al*. (2024)
	End	0.90	Baştuğ *et al*. (2024)
Chili Pepper	Initial	0.45	Pereira *et al*. (2021)
	Mid-season	1.00	Pereira *et al*. (2021)
	End	0.80	Pereira *et al*. (2021)
Strawberry	Initial	0.40	Allen *et al*. (1998)
	Mid-season	0.90	Allen *et al*. (1998)
	End	0.65	Allen *et al*. (1998)
Lettuce	Initial	0.70	Allen *et al*. (1998)
	Mid-season	1.00	Allen *et al*. (1998)
	End	0.95	Allen *et al*. (1998)
Cabbage	Initial	0.70	Allen *et al*. (1998)
	Mid-season	1.05	Allen *et al*. (1998)
	End	0.95	Allen *et al*. (1998)
Basil	Initial	0.30	Rahimi-Khoob *et al*. (2020)
	Mid-season	0.86	Rahimi-Khoob *et al*. (2020)
	End	0.76	Rahimi-Khoob *et al*. (2020)
Mint	Initial	0.35	Allen *et al*. (1998)
	Mid-season	0.85	Incrocci *et al*. (2020)
	End	0.70	Incrocci *et al*. (2020)

To ensure methodological transparency, crop coefficients (K_c) were compiled from internationally recognized sources, with priority given to lysimeter-based studies conducted under Mediterranean and arid climatic conditions. It should be noted that Kc values were not applied as fixed constants throughout the growing period; rather, they were calculated on a daily basis using linear interpolation between the initial, mid-season, and end-stage coefficients, based on the length of each growth stage for each crop. Table 7 presents the K_c values used for each crop and growth stage, along with their sources. For solanaceous crops (tomato, cucumber, eggplant, and bell pepper), coefficients were primarily adopted from Baştuğ *et al*. (2024), while coefficients for chili pepper were derived from Pereira *et al*. (2021). For leafy vegetables (lettuce, cabbage, and mint) and strawberry, coefficients were derived from FAO-56 (Allen *et al*., 1998) with greenhouse-specific modifications proposed by Incrocci *et al*. (2020). For basil, local coefficients from Rahimi-Khoob *et al*. (2020) were used to ensure regional relevance.

Daily crop evapotranspiration (ET_c) was calculated using Equation (4):

$$ET_c = K_c \times ET_{oGH} \tag{4}$$

Since effective rainfall does not occur under greenhouse conditions, the net water requirement of the crop was considered equivalent to ET_c (Baudoin *et al.*, 2017):

$$IR_{net} = ET_c \tag{5}$$

To calculate the total water requirement during the growing period, daily ET_c values were summed for all days of the growing period (from planting to harvest):

$$IR_{net,total} = \sum_{i=1}^{LGP} E\,T_{c,i} \tag{6}$$

For crops with multiple cultivation cycles per year, the annual water requirement was calculated as the sum of the water requirements of all cultivation cycles.

2.5. Statistical and Graphical Analysis

Descriptive statistical and graphical analyses were performed to evaluate the spatial variability of greenhouse crop water requirements estimated using the Almeria and Solar Radiation methods across the nine meteorological stations. Box-and-whisker plots were used to compare the distribution of water requirement estimates, including the median, interquartile range (IQR), mean, and overall variability among stations for each crop. Heat maps were generated to visualize the spatial distribution of estimated irrigation requirements and to identify regional patterns across crops and meteorological stations. Furthermore, scatter plot analysis coupled with simple linear regression was performed to evaluate the relationship and consistency between the two estimation methods. The regression equation and coefficient of determination (R^2) were used to quantify the strength of the linear association between the methods. All statistical analyses and graphical plots were generated using Microsoft Excel (version 2019).

3. Results

3.1. Water Requirement of Solanaceous Crops and Greenhouse Fruit Crops

Table 8 presents the range of net water requirement for major solanaceous greenhouse crops and strawberry in Alborz Province. The provincial averages represent the arithmetic mean of the values recorded across the nine stations, while the full range for each crop is also presented in the table. Based on expert consultations and greenhouse farmer interviews, strawberry cultivation begins in February with a full-year growing period. For solanaceous crops, the cultivation periods varied by crop type: tomato was considered from early April to late November, cucumber from early April to late August, eggplant, chili pepper and bell pepper from early February to late November. The lower and upper bounds were calculated using the solar radiation and Almeria radiation methods, respectively. As shown in Table 8, the net water requirement range for strawberry in Alborz Province varies between 955.1 and 959.7 mm.

Table 8. Range of Net Water Requirement for Solanaceous Crops and Strawberry in Alborz Province (mm per growing season)

Weather Station	Strawberry	Tomato	Cucumber	Eggplant	Chili Pepper	Bell Pepper
Karaj	996.1 - 999.7	1024.0 - 1173.2	860.3 - 935.1	1086.99 - 1208.89	980.0 - 1068.8	1103.4 - 1224.1
Hashtgerd	1024.1 - 1028.1	1057.6 - 1207.0	879.9 - 954.9	1120.5 - 1242.6	1013.5 - 1102.5	1136.9 - 1257.8
Meshkin Dasht	1067.1 - 1070.9	1088.5 - 1238.0	915.5 - 990.3	1154.8 - 1276.9	1048.0 - 1136.9	1171.4 - 1292.1
Eshtehard	1104.0 - 1113.4	1116.6 - 1269.9	943.2 - 1021.1	1189.8 - 1320.2	1086.5 - 1180.1	1209.9 - 1335.4
Nazarabad	1061.3 - 1068.7	1087.6 - 1240.0	952.2 - 991.4	1155.9 - 1281.7	1048.9 - 1141.6	1172.3 - 1296.8
Taleqan	902.3 - 905.8	953.6 - 1102.9	788.3 - 863.0	1004.3 - 1126.3	897.4 - 986.2	1020.8 - 1141.5
Payam Airport	817.1 - 820.5	866.0 - 1015.2	725.9 - 800.8	918.0 - 1039.9	811.0 - 899.8	934.4 - 1055.1
Asara	837.1 - 840.6	894.9 - 1044.1	740.0 - 814.6	941.6 - 1063.3	834.7 - 923.2	958.1 - 1078.5
Zidasht	786.3 - 789.4	844.4 - 993.7	699.1 - 773.6	888.8 - 1010.6	782.0 - 870.6	905.4 - 1025.8
Provincial Average	955.1- 959.7	992.6 - 1142.7	833.8 - 905.0	1051.2 - 1174.5	944.7 - 1034.4	1068.1 - 1189.7

For major solanaceous crops, the provincial average ranges are: bell pepper 1068.1 to 1189.7 mm, eggplant 1051.2 to 1174.5 mm, tomato 992.6 to 1142.7 mm, chili pepper 944.7 to 1034.4 mm, and cucumber 833.8 to 905.0 mm. Among solanaceous crops, bell pepper and eggplant exhibited the highest water requirements, which can be attributed to their higher mid-season crop coefficients and extended growing periods. Cucumber exhibited the lowest water requirement among solanaceous crops, consistent with its lower crop coefficient and shorter effective growing period. Strawberry, despite its full-year growing period, demonstrated a relatively moderate water requirement compared to solanaceous crops, which can be attributed to its lower crop coefficient and prostrate growth habit with smaller leaf area index.

3.2. Water Requirement of Major Greenhouse Leafy Vegetables

Table 9 presents the range of annual net water requirement for major greenhouse leafy vegetables in Alborz Province, including lettuce, cabbage, basil, and mint. Based on expert consultations, the growing periods were 90 days for lettuce and cabbage (4 cultivation cycles per year) and 45 days for basil and mint (8 cultivation cycles per year). As shown in Table 9, the annual net water requirement ranges for leafy vegetables are: cabbage 1149.7 to 1171.2 mm, lettuce 1112.9 to 1134.1 mm, mint 1046.6 to 1049.9 mm, and basil 918.1 to 929.9 mm. Cabbage and basil exhibited the highest and lowest water requirements, respectively, primarily due to differences in biomass production, crop coefficient, and growing period length. The highest values were observed at Eshtehard station, which can be attributed to higher solar radiation and temperature in this region.

Table 9. Range of Annual Net Water Requirement for Major Greenhouse Leafy Vegetables in Alborz Province (mm per year)

Weather Station	Lettuce	Cabbage	Basil	Mint
Karaj	1154.0-1174.2	1191.0-1211.3	958.4 - 970.1	1092.4 - 1093.6
Hashtgerd	1182.0-1202.5	1216.2-1239.6	991.3 - 1001.1	1125.3 - 1126.2
Meshkin Dasht	1224.7-1245.4	1262.1-1282.5	1031.1 - 1042.7	1163.5 - 1165.5
Eshtehard	1261.9-1287.9	1298.9-1325.0	1077.2 - 1088.1	1173.6 - 1179.2
Nazarabad	1219.2-1243.2	1256.2-1280.2	1032.7 - 1041.9	1149.5 - 1146.4
Taleqan	1060.2-1080.3	1097.2-1117.4	859.3 - 871.1	994.2 - 995.6
Payam Airport	975.0-995.0	1012.1-1032.1	772.7 - 788.0	908.7 - 910.5
Asara	995.0-1015.0	1032.0-1052.1	794.2 - 806.1	929.7 - 931.2
Zidasht	944.7-963.9	981.2-1001.0	746.6 - 758.5	876.9 - 879.5
Provincial Average	1112.9-1134.1	1149.7-1171.2	918.1 - 929.9	1046.6 - 1049.9

3.4. Spatial Variability Analysis of Water Requirements

To investigate factors influencing spatial variations in water requirements across the province, box-and-whisker plots, heat maps, and scatter plot analysis were employed. Figure 2 presents the box-and-whisker plots of greenhouse crop water requirements estimated using the Almeria and Solar Radiation methods across the nine meteorological stations for the ten evaluated greenhouse crops.

Overall, the Almeria method generally produced higher median greenhouse crop water requirement estimates than the Solar Radiation method across the evaluated crops, indicating a systematic tendency of this approach to estimate greater water demands under greenhouse conditions. Despite these differences in magnitude, both methods exhibited broadly comparable distributional patterns, suggesting that they similarly captured the spatial variability of crop water requirements among the meteorological stations.

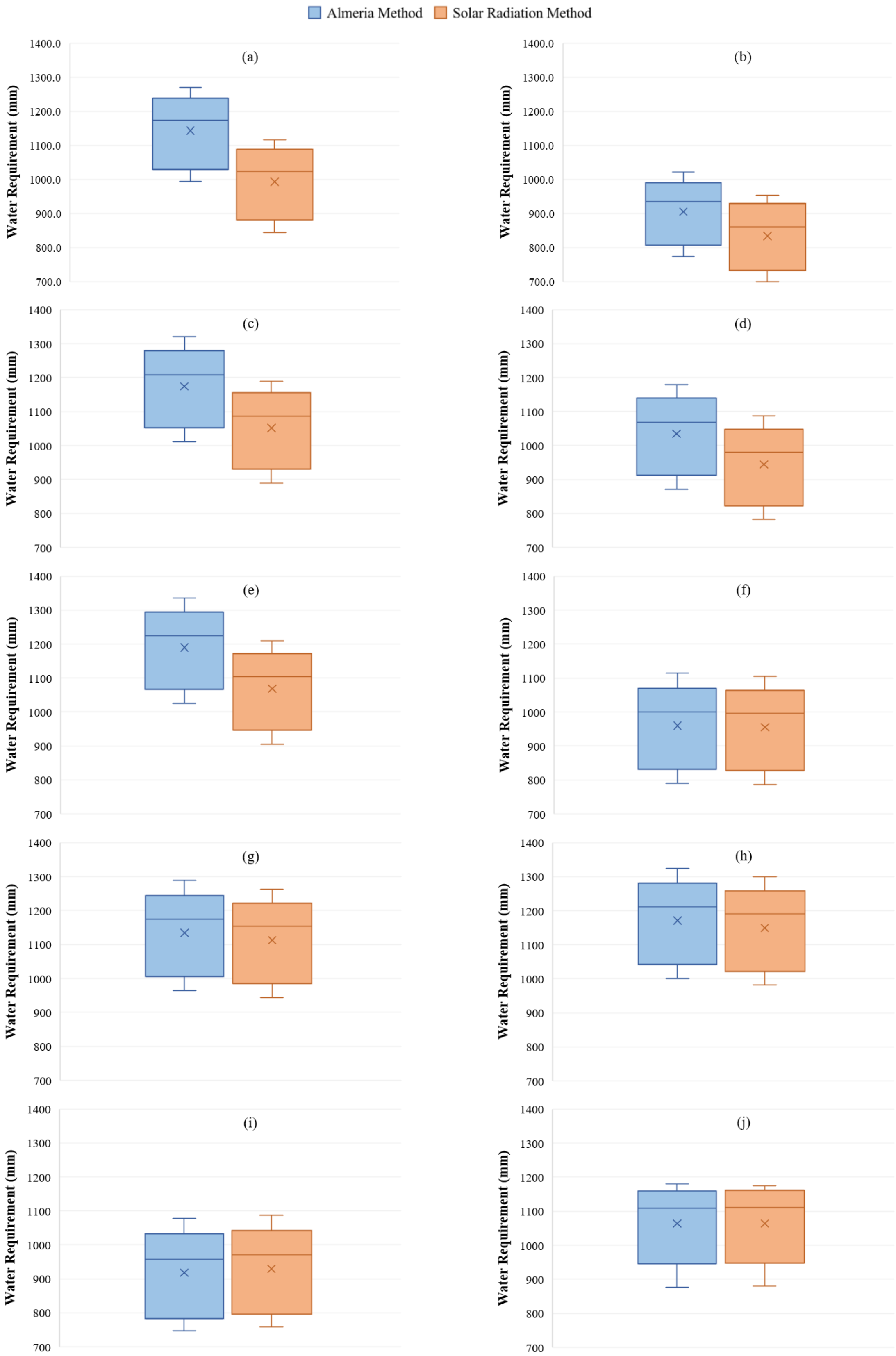

Figure 2. Box-and-whisker plots illustrating the spatial variability of greenhouse crop water requirements estimated using the Almeria and Solar Radiation methods across nine meteorological stations for (a) tomato, (b) cucumber, (c) eggplant, (d) chili pepper, (e) bell pepper, (f) strawberry, (g) lettuce, (h) cabbage, (i) basil, and (j) mint. In each box plot, the horizontal line inside the box represents the median, the box boundaries indicate the first (Q1) and third (Q3) quartiles, the whiskers represent the minimum and maximum values within 1.5 × the interquartile range (IQR), and the × symbol denotes the mean value.

Among the investigated crops, eggplant (c) and bell pepper (e) showed the widest interquartile ranges (IQRs) and highest median values, indicating greater spatial heterogeneity and higher water requirements across the study area (ranging from approximately 889 to 1320 mm for eggplant and 905 to 1335 mm for bell pepper). Tomato (a) exhibited moderate IQRs with a range of approximately 844 to 1270 mm, while cucumber (b) showed a slightly narrower range of approximately 699 to 1021 mm. Chili pepper (d) and strawberry (f) exhibited relatively narrow IQRs, reflecting more homogeneous spatial distribution of water requirements, with ranges of approximately 782 to 1180 mm and 786 to 1113 mm, respectively. Among leafy vegetables, cabbage (h) and lettuce (g) exhibited relatively high-water requirements with moderate IQRs (ranging from approximately 981 to 1325 mm for cabbage and 944 to 1288 mm for lettuce), whereas basil (i) and mint (j) showed the lowest values with narrow IQRs (ranging from approximately 747 to 1088 mm for basil and 877 to 1179 mm for mint). The separation between the medians of the two methods was most pronounced for tomato (a), eggplant (c), and bell pepper (e), whereas strawberry (f), basil (i), and mint (j) displayed substantial overlap between the two distributions, indicating closer agreement between the Almeria and Solar Radiation methods for these crops. This can be attributed to the higher crop coefficients and denser canopies of tomato, eggplant, and bell pepper, which amplify the sensitivity of water requirement estimates to methodological differences.

This closer agreement for strawberry, basil, and mint can be attributed to their lower crop coefficients and more uniform growth habits, which reduce the sensitivity of water requirement estimates to methodological differences. No pronounced outliers were observed in any crop, indicating that none of the meteorological stations exerted an excessive influence on the overall distribution of estimated water requirements. Consequently, the observed variability primarily reflects genuine spatial differences in climatic conditions rather than anomalous observations. Overall, the box plots demonstrate that although the Almeria method generally predicts higher greenhouse crop water requirements, both estimation methods preserve similar spatial variability patterns across the nine meteorological stations. Therefore, the principal difference between the two methods lies in the magnitude of the estimated water requirement rather than in the spatial distribution of water demand.

To further visualize the spatial distribution of water requirements, Figure 3 presents heat maps of greenhouse crop water requirements estimated using the Almeria and Solar Radiation methods across the nine meteorological stations. Both methods revealed a highly consistent spatial distribution pattern, indicating that the relative variation in water requirements among stations was preserved irrespective of the estimation method. A clear and consistent spatial gradient in greenhouse crop water requirements was observed across the study area. The highest water requirements were consistently recorded at Eshtehard, Nazarabad, and Meshkin Dasht, whereas the lowest values were generally recorded at Taleqan, Asara, Payam Airport and Zidasht.

Intermediate water requirements were estimated for Karaj (S4) and Hashtgerd (S5), forming a gradual spatial transition that reflects coherent regional patterns rather than isolated local fluctuations. Crop-specific differences were also evident in both heat maps. Cabbage, tomato, bell pepper, eggplant, cucumber, and lettuce consistently exhibited the highest water requirements across most stations, whereas basil, chili pepper, strawberry, and mint required substantially less water. The persistence of this ranking across both estimation methods indicates that crop-specific water demand remained stable despite methodological differences. Although the Almeria method systematically produced higher numerical estimates than the Solar Radiation method, the two methods exhibited remarkably similar spatial distribution patterns. Stations with relatively high or low water requirements under one method maintained the same ranking under the other, confirming that the primary difference between the methods lies in the magnitude of the estimates rather than the spatial pattern of water demand. The smooth spatial transition across the meteorological stations, with no abrupt changes between neighboring sites, suggests that the estimated water requirements primarily reflect regional climatic gradients rather than localized or anomalous conditions.

To quantitatively evaluate the relationship and consistency between the two estimation methods, Figure 4 presents a scatter plot of greenhouse crop water requirements estimated using the Solar Radiation and Almeria methods for all evaluated crops across the nine meteorological stations ($n = 90$). A strong positive linear relationship was observed between the two estimation methods, indicating that both approaches consistently captured the variability in greenhouse crop water requirements across different climatic conditions. The linear regression analysis yielded the equation $y=0.9939x+65.283$ with a coefficient of determination of R2=0.86, indicating that approximately 86.1% of the variability in the Almeria estimates can be explained by the corresponding estimates obtained using the Solar Radiation method. The relationship was statistically significant ($p < 0.001$). This strong correlation demonstrates a high level of consistency between the two estimation approaches. The regression slope (0.9939) being close to unity indicates that, on average, the Almeria method produces estimates nearly proportional to the Solar Radiation method, with only a slight systematic difference. Furthermore, the intercept (65.28 mm) suggests a modest positive offset, implying that the Almeria method tends to produce slightly higher estimates, particularly at lower water requirement values.

Crop	S1	S2	S3	S4	S5	S6	S7	S8	S9
Tomato	1269.9	1240.0	1238.0	1173.2	1207.0	1102.9	1044.1	1015.2	993.7
Cucumber	1021.1	991.4	990.3	935.1	954.9	863.0	814.6	800.8	773.6
Eggplant	1320.2	1281.7	1276.9	1208.9	1242.6	1126.3	1063.3	1039.9	1010.6
Chili Pepper	1180.1	1141.6	1136.9	1068.8	1102.5	986.2	923.2	899.8	870.6
Bell Pepper	1335.4	1296.8	1292.1	1224.1	1257.8	1141.5	1078.5	1055.1	1025.8
Strawberry	1113.4	1068.7	1070.9	999.7	1028.1	905.8	840.6	820.5	789.4
Lettuce	1287.9	1243.2	1245.4	1174.2	1202.5	1080.3	1015.0	995.0	963.9
Cabbage	1325.0	1280.2	1282.5	1211.3	1239.6	1117.4	1052.1	1032.1	1001.0
Basil	1077.2	1032.6	1031.1	958.4	991.3	859.3	794.2	772.7	746.6
Mint	1179.2	1149.5	1163.5	1092.4	1125.3	994.2	929.7	908.7	876.9

(a)

Crop	S1	S2	S3	S4	S5	S6	S7	S8	S9
Tomato	1116.6	1087.6	1088.5	1024.0	1057.6	953.6	894.9	866.0	844.4
Cucumber	943.2	952.2	915.5	860.3	879.9	788.3	740.0	725.9	699.1
Eggplant	1189.8	1155.9	1154.8	1087.0	1120.5	1004.3	941.6	918.0	888.8
Chili Pepper	1086.5	1048.9	1048.0	980.0	1013.5	897.4	834.7	811.0	782.0
Bell Pepper	1209.9	1172.3	1171.4	1103.4	1136.9	1020.8	958.1	934.4	905.4
Strawberry	1104.0	1061.3	1067.1	996.1	1024.1	902.3	837.1	817.1	786.3
Lettuce	1261.9	1219.2	1224.7	1154.0	1182.0	1060.2	994.9	975.0	944.2
Cabbage	1298.9	1256.2	1262.1	1191.0	1216.2	1097.2	1032.0	1012.1	981.2
Basil	1088.1	1041.9	1042.7	970.1	1001.1	871.1	806.1	786.0	758.5
Mint	1173.6	1146.4	1165.5	1093.6	1126.2	995.6	931.2	910.5	879.5

(b)

Water Requirement (mm): 1400, 1350, 1300, 1250, 1200, 1150, 1100, 1050, 1000, 950, 900, 850, 800, 750

Figure 3. Heat maps showing the spatial distribution of greenhouse crop water requirements estimated using the (a) Almeria and (b) Solar Radiation methods for ten greenhouse crops across nine meteorological stations (S1 = Eshtehard, S2 = Nazarabad, S3 = Meshkin Dasht, S4 = Karaj, S5 = Hashtgerd, S6 = Taleqan, S7 = Asara, S8 = Payam Airport, and S9 = Zidasht)

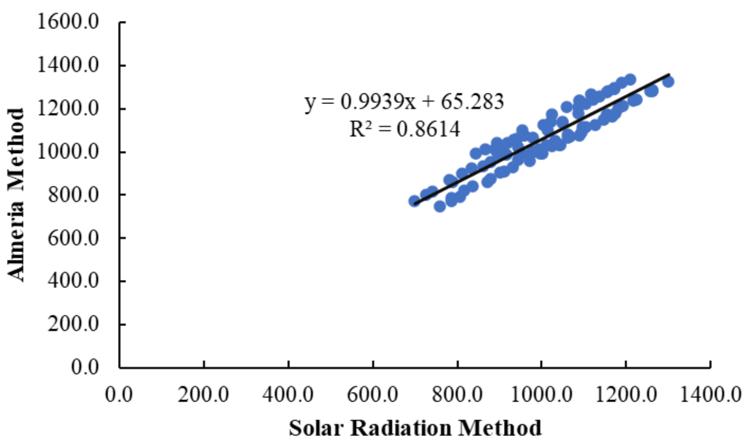

Figure 4. Scatter plot illustrating the relationship between greenhouse crop water requirements estimated using the Solar Radiation and Almeria methods across ten greenhouse crops and nine meteorological stations (n = 90). The solid line represents the least-squares linear regression, and the regression equation and coefficient of determination (R^2) are shown.

This is consistent with the box plots and heat maps, which demonstrated similar spatial distribution patterns while revealing modest differences in the magnitude of estimated water requirements. Although minor deviations from the regression line are evident, the majority of observations are closely clustered around the fitted relationship, indicating a stable agreement between the two methods across different crops and meteorological stations. These findings confirm that the Almeria and Solar Radiation methods provide highly consistent estimates of greenhouse crop water requirements, with differences largely reflecting slight systematic variations in estimation magnitude rather than inconsistencies in the spatial pattern of water demand.

To further evaluate the agreement between the two methods, bias analysis was performed. The mean bias (Almeria – Solar Radiation) was 61.8 mm, with RMSE = 81.7 mm and MAE = 61.8 mm. These metrics confirm that the Almeria method systematically overestimates water requirements compared to the Solar Radiation method, with relatively consistent differences across the range of values.

3. Discussion

The present study employed two complementary radiation-based methods to estimate the net water requirement of major greenhouse crops in Alborz Province. The results demonstrated a strong linear correlation between the Almeria and Solar Radiation methods ($R^2 = 0.86$), confirming that both approaches consistently captured the spatial and crop-specific variability in water requirements. However, the Almeria method consistently produced higher estimates across all crops and stations, with an average overestimation of approximately 10-15% compared to the Solar Radiation method. The bias analysis further supports this finding, with a mean bias of 61.8 mm, RMSE of 81.7 mm, and MAE of 61.8 mm, indicating that the Almeria method consistently produces higher estimates than the Solar Radiation method. This systematic difference can be attributed to the structural and operational parameters incorporated in the Almeria method, such as greenhouse cover transmissivity, shading screens, and the age of covering materials (Fernández *et al*., 2010; Bonachela *et al*., 2006). The Almeria method, originally developed for plastic greenhouses, accounts for radiative components that influence evapotranspiration inside greenhouses more comprehensively than the simpler Solar Radiation method (Baille, 1996). The larger gap between the two methods for tomato, eggplant, and bell pepper can be attributed to their higher crop coefficients and extended growing periods, which amplify the systematic differences in radiative estimation approaches. These crops have denser canopies and longer growing seasons, making them more sensitive to the additional radiative components accounted for by the Almeria method. Despite these numerical differences, the high correlation coefficient and the consistent spatial ranking of stations across both methods indicate that the choice between the two methods does not significantly affect the relative assessment of water requirements among crops or locations. This finding is particularly important for practical applications, as it suggests that both methods can be used interchangeably for comparative purposes, provided that the systematic bias is considered when determining absolute irrigation volumes. Similar findings were reported by Fernández *et al*. (2010, 2009) in Mediterranean greenhouses, where multiple ET_o estimation methods were compared and found to produce consistent spatial patterns despite variations in absolute values.

The results revealed considerable variation in water requirements among the ten evaluated crops, ranging from 833.8 mm for cucumber to 1,189.7 mm for bell pepper (provincial averages). This range is consistent with findings from lysimeter-based studies conducted under similar greenhouse conditions, which have reported mid-season crop coefficients (K_c mid) of 1.4–1.9 for solanaceous crops in Mediterranean plastic greenhouses (Baştuğ *et al*., 2024). The relatively high-water requirements observed for tomato, eggplant, and bell pepper in our study align with these reported coefficients, reflecting the high evaporative demand and extended growing periods characteristic of these crops. Conversely, the moderate water requirements observed for chili pepper and strawberry are consistent with the lower crop coefficient values (K_c mid: 0.5–1.35) reported for vegetable crops in hyper-arid greenhouse environments (Al Tamimi *et al*., 2022), where reduced humidity and high temperatures influence crop water demand. Among solanaceous crops, bell pepper exhibited the highest water requirement (1068.1 - 1189.7 mm), followed by eggplant (1051.2 - 1174.5 mm), tomato (992.6 - 1142.7 mm), chili pepper (944.7 - 1034.4 mm), and cucumber (833.8 - 905.0 mm). The relatively high-water requirement of eggplant and bell pepper can be attributed to their higher mid-season crop coefficients and relatively longer growing periods. Chili pepper exhibited a lower water requirement, consistent with its slightly shorter growing period compared to the other solanaceous crops. This finding is consistent with the lysimeter-based study of Rezaverdinejad *et al*. (2017), who reported that tomato required significantly more water than cucumber under similar greenhouse conditions. Strawberry, despite its full-year growing period, exhibited a moderate water requirement (955.1 - 959.7 mm) comparable to chili pepper. This relatively low water requirement can be attributed to its prostrate growth habit, smaller leaf area index, and lower crop coefficient compared to solanaceous crops. Similar findings were reported by FAO-56 guidelines (Allen *et al*., 1998), which assign relatively low crop coefficients to strawberry under standard conditions. Among leafy vegetables, cabbage exhibited the highest water requirement (1149.7 - 1171.2 mm), followed by lettuce (1112.9 - 1134.1 mm), mint (1046.6 - 1049.9 mm), and basil (918.1 - 929.9 mm). The higher water requirement of cabbage and lettuce compared to basil and mint can be attributed to their larger biomass production, higher crop coefficients, and longer growing periods (90 days vs. 45 days). This pattern is consistent with the findings of Incrocci *et al*. (2020), who reviewed adaptations of the FAO56 approach for greenhouse conditions and reported that crop coefficient (K_c) values and water requirements vary considerably among vegetable types, with leafy vegetables generally exhibiting higher water demand than aromatic herbs due to differences in canopy development, harvestable biomass, and growing cycle length (Incrocci *et al*., 2020). Additionally, Pereira *et al*. (2021) updated the FAO56 single and basal crop coefficients for vegetable crops, confirming that leafy vegetables (e.g., cabbage, lettuce) have higher Kc values and water requirements compared to herbs and spices (e.g., basil, mint) due to differences in canopy cover, stomatal conductance, and harvest index (Pereira *et al*., 2021).

The most striking finding of this study was the clear spatial gradient in water requirements across the province, with the highest values consistently recorded at Eshtehard, Nazarabad , and Meshkin Dasht, and the lowest values at Zidasht, Asara, Taleqan, and Payam Airport (S9). This gradient was consistently observed across all crops and both estimation methods, confirming that the observed spatial patterns are robust and not method-dependent. The substantial difference in water requirements between these groups of stations—approximately 300 mm for tomato between Eshtehard and Zidasht—reflects the influence of climatic factors, particularly temperature and solar radiation, on evapotranspiration rates inside greenhouses. Intermediate water requirements were estimated for Karaj and Hashtgerd, forming a gradual spatial transition that reflects coherent regional patterns rather than isolated local fluctuations. This smooth transition across the province, together with the absence of abrupt changes between neighboring stations, suggests that the estimated water requirements primarily reflect regional climatic gradients rather than localized or anomalous site-specific conditions. These findings are consistent with the spatial variability patterns reported by Zarei *et al*. (2018) for cucumber across different climatic zones in Iran, and by Fernández *et al*. (2010) for greenhouse crops in Spain in Mediterranean region. The practical implications of this spatial variability are substantial. For greenhouse developers and policymakers, these findings suggest that water resource allocation and crop selection should be tailored to the specific climatic conditions of each location. In warm, low-elevation areas where water requirements are higher, priority should be given to crops with lower water requirements (e.g., chili pepper, strawberry, basil) or to the adoption of water-saving technologies such as regulated deficit irrigation. In contrast, cold, high-elevation areas with lower water requirements may be more suitable for high-water-demand crops such as tomato, cabbage, or bell pepper. A lysimeter study by AsliCharandabi *et al*. (2025) in Varamin, Iran, under greenhouse conditions reported an annual evapotranspiration of 761 mm (7,612 m^3 ha^{-1}) for bell pepper. This value is lower than our provincial average range for bell pepper (1,068 - 1,190 mm). The difference can be primarily attributed to the shorter growing period in the Varamin study (130 days) compared to the full cultivation cycle considered in our research, which reflects local practices in Alborz Province.

The results of this study offer several methodological considerations for greenhouse water management. First, the strong correlation between the Almeria and Solar Radiation methods suggests that either approach may be used for estimating crop water requirements, provided that the systematic bias is accounted for. For practical applications where absolute values are needed, method selection should consider local conditions, data availability, and the specific objectives of the irrigation plan. Second, the spatial variability analysis indicates that water requirements are highly location-specific, even within a relatively small province such as Alborz, underscoring the importance of localized climatic data for irrigation planning. Third, the comparison of water requirements across crops provides a basis for cropping pattern optimization. In water-limited areas, growers may prioritize crops with lower water requirements (e.g., chili pepper, strawberry, basil) over high-water-demand crops (e.g., tomato, cabbage, bell pepper). Alternatively, regulated deficit irrigation strategies, such as those tested by Jafari Najafabadi *et al*. (2022) for bell pepper (80% of water requirement), could be considered to reduce water consumption while maintaining acceptable yields. The data provided in this study can serve as a reference for designing such strategies. In addition, this study is based on model-based estimations. Further lysimeter studies are encouraged to complement and expand upon the findings presented here.

Conclusion

This study provides the first comprehensive assessment of net water requirements for major greenhouse crops in Alborz Province, covering ten economically important species across three distinct groups: solanaceous crops (tomato, cucumber, eggplant, chili pepper, and bell pepper), leafy vegetables (lettuce, cabbage, basil, and mint), and greenhouse fruit crops (strawberry). Reference evapotranspiration inside greenhouses was estimated using long-term meteorological data from nine weather stations across the province, employing both the Almeria Radiation method and the Solar Radiation method. Crop water requirements were subsequently determined by applying crop coefficients derived from authoritative international sources.

The results revealed considerable variation in water requirements among the evaluated crops, ranging from 833.8 mm for cucumber to 1,189.7 mm for bell pepper (provincial averages). A clear spatial gradient in water requirements was observed across the province, with the highest values consistently recorded at Eshtehard, Nazarabad, and Meshkin Dasht, and the lowest values at Taleqan, Asara, and Zidasht. This gradient reflects the dominant influence of climatic factors—particularly temperature and solar radiation—on evapotranspiration rates inside greenhouses. Stations with higher temperatures and greater solar radiation exhibited increased evaporative demand and, consequently, higher water requirements, whereas stations with lower temperatures and reduced solar radiation showed substantially lower requirements. This trend highlights the determining role of climatic elements, especially temperature, radiation, and humidity, in explaining spatial variations in greenhouse crop water requirements across the province.

The findings of this study offer several practical applications for greenhouse stakeholders in Alborz Province. The crop-specific and location-specific water requirement data provide a preliminary reference for irrigation planning, water allocation, greenhouse licensing, and cropping pattern optimization. By replacing generalized estimates with localized data, growers and decision-makers can reduce water waste, improve water productivity, and enhance the economic and environmental sustainability of greenhouse production. Reliance on non-local estimates can lead to inefficient water use and the depletion of already scarce water resources. The data generated in this study can assist authorities in making evidence-based decisions regarding licensing, water allocation, and development planning tailored to the actual needs of each crop. This approach not only conserves water and boosts productivity but also strengthens growers' awareness of the economic value of water and promotes more responsible consumption practices. Furthermore, the results serve as a practical tool for prioritizing greenhouse crops based on their compatibility with available water resources and for steering greenhouse expansion toward sustainable pathways.

In conclusion, this study provides a comprehensive database of estimated water requirements for greenhouse crops in Alborz Province, offering a useful preliminary reference for policymakers, extension agents, and growers. The integration of these data into irrigation planning, water resource management, and greenhouse development policies may contribute to improved water productivity and more sustainable greenhouse agriculture in the region.

Conflict of interest

The authors declare no conflict of interest.

Acknowledgments

The authors gratefully acknowledge the Agricultural Jihad Organization of Alborz Province, Iran, for funding this research (Project No. 124-14-14-021-03021-030535; Grant No. 12/33/02/42061). The authors also sincerely thank Eng. Firoozbakht for her valuable scientific and technical assistance throughout this study.

References

Alborz Province Agricultural Jihad Organization. 2023. *Statistical report on greenhouse cultivation in Alborz Province*. Agricultural Jihad Organization of Alborz Province, Iran. (in Persian)

Allen, R. G., Pereira, L. S., Raes, D., & Smith, M. 1998. *Crop evapotranspiration-Guidelines for computing crop water requirements-FAO Irrigation and drainage paper 56*. Fao, rome, 300(9), D05109. ISBN 92-5-104219-5

Al Tamimi, M., Green, S., Hammami, Z., Ammar, K., Al Ketbi, M., Al-Shrouf, A. M., ... & Clothier, B. 2022. Evapotranspiration and crop coefficients using lysimeter measurements for food crops in the hyper-arid United Arab Emirates. *Agricultural Water Management*, *272*, 107826. https://doi.org/10.1016/j.agwat.2022.107826

Arvin, S. M. J., Salari, E., & Soufi, H. R. 2026. Influence of salicylic acid concentrations and spraying times on growth and physiology of eggplant. *Greenhouse Plant Production Journal,* 3(2), 1-17. https://doi.org/10.66224/gppj.3.2.1(in Persian)

Asli Charandabi, M. R., Mahjoobi, E., & Abdolabadi, H. 2025. Estimation of evapotranspiration and crop coefficient for bell pepper using the weighing method and empirical models (Case study: Hesargoli greenhouse, Varamin). *Irrigation and Water Engineering*, 15(3), 151-167. https://doi.org/10.22125/iwe.2025.496217.1848

Averbuch, N., & Moshelion, M. 2024. Evaluating evapotranspiration in a commercial greenhouse: A comparative study of microclimatic factors and machine-learning algorithms. *bioRxiv*. https://doi.org/10.1101/2024.01.11.575151

Azadsharaki, F., Javadi Moghaddam, J., & Zarei, G. 2021. *Recognition and application conditions of greenhouse cover* (Technical Manual No. 59803). Agricultural Engineering Research Institute. (in Persian)

Baille, A. 1996. Principles and methods for predicting crop water requirement in greenhouse environments. *Cahier Options Méditerranéennes*, *31*, 177-187.

Baştuğ, R., Büyüktaş, D., Büyüktaş, K., Aydinsakir, K., Onus, A. N., & Karaca, C. 2024. Evapotranspiration and crop coefficients of some vegetable crops grown under greenhouse conditions. *Journal of Water and Climate Change*, 15(7), 3236-3259. https://doi.org/10.2166/wcc.2024.024

Baudoin, W., Nersisyan, A., Shamilov, A., Hodder, A., Gutierrez, D., De Pascale, S., Nicola, S., Gruda, N., Urban, L., & Tanny, J. 2017. *Good Agricultural Practices for greenhouse vegetable production in the South East European countries: Principles for sustainable intensification of smallholder farms* (FAO Plant Production and Protection Paper No. 230, Vol. 230, pp. 1-449). FAO. https://doi.org/10.4060/22b737e1-en (ISBN 978-92-5-109622-2)

Bayat, P., & Bayat, P. 2025. Deep learning–driven adaptive framework for precision greenhouse management based on species-specific needs. *Greenhouse Plant Production Journal,* 2(4), 28. https://doi.org/10.61882/gppj.2.4.28 (in Persian)

Bonachela, S., González, A. M., & Fernández, M. D. 2006. Irrigation scheduling of plastic greenhouse vegetable crops based on historical weather data. *Irrigation Science*, 25(1), 53-62. https://doi.org/10.1007/s00271-006-0034-z

Cemek, B., & Demir, Y. 2005. Testing of the condensation characteristics and light transmissions of different plastic film covering materials. *Polymer Testing*, 24(3), 284-289. https://doi.org/10.1016/j.polymertesting.2004.11.006

Dehghanpir, S., Bazrafshan, O., Ramezani Etedali, H., Holisaz, A., & Collins, B. 2024. Water scarcity assessment in Iran's agricultural sector using the water footprint concept. *Environment, Development and Sustainability*, 26(11), 28995-29020. https://doi.org/10.1007/s10668-023-03852-3

Delavar, A., Mirlatifi, S. M., & Zarei, G. 2015. Water requirement and crop coefficient of Polianthes tuberose L. in Varamin. *Iranian Journal of Irrigation and Drainage*, 9(3), 480-488. (in Persian)

Ebrahimi, M., Rezaverdinejad, V., Besharat, S., & Abdi, M. 2018. A study of evapotranspiration as well as crop coefficient in Ocimum Basilicum L. growth process in greenhouse. *Journal of Water and Irrigation Management*, 8(1), 1-13. (in Persian)

Eshghi, S., Sarikhani, S., Shirdel, M., Davarzani, M., & Hosseini, S. 2026. The significance of controlled environments in shaping the future of fruit cultivation. *Journal of Greenhouse and Plant Production*, 1(4), 11. https://doi.org/10.61186/gppj.1.4.11. (in Persian)

Fernández, M. D., Bonachela, S., Orgaz, F., Thompson, R., López, J. C., Granados, M. R., Gallardo, M., & Fereres, E. 2010. Measurement and estimation of plastic greenhouse reference evapotranspiration in a Mediterranean climate. *Irrigation Science*, 28(6), 497-509. https://doi.org/10.1007/s00271-010-0210-z

Fernández, M.D., Baeza, E., Céspedes, A., Pérez-Parra, J., & Gázquez, J.C. 2009. Validation of on-farm crop water requirements (PrHo) model for horticultural crops in an unheated plastic greenhouse. *Acta Horticulturae*, 807, 295-300. https://doi.org/10.17660/ActaHortic.2009.807.41

Fernández, M.D., Orgaz, F., Fereres, E., López, J.C., Céspedes, A., Pérez-Parra, J., Bonachela, S., & Gallardo, M. 2001. *Programación del riego de cultivos hortícolas bajo invernadero en el sudeste español*. Cajamar (Caja Rural Intermediterránea).

Gaafer, A. M. E. A., Mohammed, H. I., & Elfadil, A. D. 2024. Estimating reference evapotranspiration using Penman-Monteith (FAO-56-PM) method from limited data in fan and pad greenhouses. *World News of Natural Sciences*, 53, 49-59.

Gaafer, A. M. E. A., & Mohammed, H. I. 2024. Estimating fan and pad greenhouse reference evapotranspiration using FAO-56-Penman-Monteith and a simplified heat transfer approach for predicting internal temperature. *World News of Natural Sciences*, 53, 140-151.

Incrocci, L., Thompson, R. B., Fernandez-Fernandez, M. D., De Pascale, S., Pardossi, A., Stanghellini, C., Rouphael, Y., & Gallardo, M. 2020. Irrigation management of European greenhouse vegetable crops. *Agricultural Water Management*, 242, 106393. https://doi.org/10.1016/j.agwat.2020.106393

Katsoulas, N., & Stanghellini, C. 2019. Modelling crop transpiration in greenhouses: Different models for different applications. *Agronomy*, 9(7), 392. https://doi.org/10.3390/agronomy9070392

Keykhaei, F., Zarei, G., Ganji Khorramdel, N., & Sadeghi, S. 2020. Determination of water requirement of rose cultivars in hydroponic greenhouse. *Journal of Water Research in Agriculture*, 34(4), 531-542. (in Persian)

Khorsandi, M., Omidi, T., & van Oel, P. 2023. Water-related limits to growth for agriculture in Iran. *Heliyon*, 9(5), e16132. https://doi.org/10.1016/j.heliyon.2023.e16132

Khoshsimaie Chenar, M., Noory, H., Liaghat, A., Soltani Salehabadi, F., & Motesharezadeh, B. 2025. Evaluation of the accuracy of different machine learning algorithms in predicting greenhouse cucumber crop evapotranspiration. *Journal of Water and Irrigation Management*, 15(3), 563-683. https://doi.org/10.22059/jwim.2025.382501.1100

Maraveas, C., Kotzabasaki, M. I., Bayer, I. S., & Bartzanas, T. 2023. Sustainable greenhouse covering materials with nano-and micro-particle additives for enhanced radiometric and thermal properties and performance. *AgriEngineering*, 5(3), 1347-1377. https://doi.org/10.3390/agriengineering5030085

Moradi, M., Ghasemi, J., Aramyan, L., & Barati, A. A. 2026. Unraveling the challenges of knowledge and technology adoption within Iranian greenhouse farming. *Results in Engineering*, 31, 111357. https://doi.org/10.1016/j.rineng.2026.111357

Mozafari, M., Abbasifar, A., & ValizadehKaji, B. 2026. Quantitative, qualitative, and physicochemical characteristics of tomato as affected by foliar application of potassium silicate. *Greenhouse Plant Production Journal*, 3(1), 68-76. https://doi.org/10.66224/gppj.3.1.68 (in Persian)

Nikbakht, J., Hamed, Z., & Mokhtari, H. 2022. Determination of Sedum (Sedum cv. nevii) water requirement, crop coefficient, and water productivity in greenhouse conditions. *Journal of Water and Sustainable Development*, 9(2), 87-94. (in Persian)

Nikolaou, G., Neocleous, D., Katsoulas, N., & Kittas, C. 2019. Irrigation of greenhouse crops. *Horticulturae*, 5(1), 7. https://doi.org/10.3390/horticulturae5010007

Nouri, M., Homaee, M., Pereira, L. S., & Bybordi, M. 2023. Water management dilemma in the agricultural sector of Iran: A review focusing on water governance. *Agricultural Water Management*, 288, 108480. https://doi.org/10.1016/j.agwat.2023.108480

Pereira, L. S., Paredes, P., López-Urrea, R., Hunsaker, D. J., Mota, M., & Shad, Z. M. 2021. Standard single and basal crop coefficients for vegetable crops, an update of FAO56 crop water requirements approach. *Agricultural Water Management*, 243, 106196. https://doi.org/10.1016/j.agwat.2020.106196

Rahimikhoob, H., Sohrabi, T., & Delshad, M. 2020. Determination of water requirement and crop coefficient for basil (*Ocimum basilicum* L.) under controlled greenhouse. *Iranian Journal of Soil and Water Research*, 50(10), 2465-2472. https://doi.org/10.22059/IJSWR.2019.280405.668191 (in Persian)

Rezaverdinejad, V., Shabanian, M., Besharat, S., & Hassani, A. 2017. Determination of crop water requirement, crop coefficient and water use efficiency of greenhouse-grown cucumber and tomato (Case study: Urmia region). *Journal of Soil and Plant Interactions*, 8(3), 27-39. (in Persian)

Rezvani, S. M., Zarei, G., & Salemi, H. R. 2022. Evapotranspiration and crop coefficient of greenhouse cucumber in Hamedan region. *Iranian Journal of Irrigation and Drainage*, 16(5), 904-916. (in Persian)

Sepehri, S., Zarei, G., Azadsharaki, F., Rezvani, S. M., & Badrzadeh, D. 2026. *Determination of water requirements for greenhouse crops in Alborz Province* (Research Report No. 124-14-14-021-03021-030535). Agricultural Engineering Research Institute. (in Persian)

Shojaei-Nia, M., Soufi, H. R., Jabbari, M., & Mousavi-Fard, S. 2026. Stress-aware greenhouse climate control: Integrating plant physiology, intelligent environmental control, and energy management for sustainable protected horticulture. *Greenhouse Plant Production Journal,* 3(2), 62-81. https://doi.org/10.66224/gppj.3.2.62 (in Persian)

Sujitha, E., Shanmugasundaram, K., & Thiyagarajan, G. 2020. Estimation of crop coefficient for Marigold (*Tagetes erecta* (L.)) under drip irrigated greenhouse. *Journal of Applied and Natural Science*, 12(2), 128-132. https://doi.org/10.31018/jans.vi.2264

Toyin, F. J., Miguel, R. J., Gbenro, O. P., & Ebenezer, A. A. 2015. Greenhouse evapotranspiration and crop factor of *Amaranthus cruentus* grown in weighing lysimeters. *African Journal of Agricultural Research*, 10(34), 3453-3461. https://doi.org/10.5897/AJAR2014.8886

Zarei, G., Salemi, H. R., Rezvani, S. M., & Esfandiari, M. 2018. *Determination of water requirement of greenhouse cucumber across the country* (Final Research Report No. 54247). Agricultural Engineering Research Institute. (in Persian)

Yuan, X., Zhou, Y., Zhou, S., & Wang, F. 2025. Agricultural and energy sectors dominate Iran’s water crisis: A GRACE-GLDAS quantification (2002–2023). *Acta Geodynamica et Geomaterialia*, 22(3), 393-404. https://doi.org/10.13168/AGG.2025.0027