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Actual water consumption index of horticultural and field crops in Iran: classification into high- and low -water consuming categories

Niaz Ali Ebrahimipak and Azadeh Sedaghat*

Soil and Water Research Institute, Agricultural Research, Education and Extension Organization (AREEO), Karaj, Iran.

Abstract

Water scarcity is a critical threat to agricultural sustainability in arid and semi-arid regions. Iran, receiving only 240 mm of annual precipitation on average, faces severe and growing pressure on its water resources, with agriculture accounting for the bulk of freshwater withdrawals. Under such conditions, accurately quantifying the actual water consumption (WRa) of crops is essential for sustainable water resource management and cropping pattern reform. This study calculated and classified the WRa for 83 field and horticulture crops across Iran, using a 10-year national dataset (2013–2023) and a mean WRa threshold of 600 mm to distinguish high water-consuming (HWC) from low water-consuming (LWC) crops. Results showed that 44 crops were classified as HWC and 28 as LWC. Among field crops, sugarcane (*Saccharum officinarum*; 3,046.8 mm), alfalfa (*Medicago sativa;* 1,603.9 mm) and Paddy rice (*Oryza sativa;* 1,249.0) exhibited the highest WRa, while carrot (255.6 mm) and celery (269.5 mm) were the lowest. Among horticulture crops, papaya (*Carica papaya*; 1,387.6 mm) and date palm (*Phoenix dactylifera*; 1,286.4 mm) exhibited the highest WRa values, followed by banana (*Musa acuminata*; 1,217.0 mm) and Sapodilla (*Manilkara zapota*; 1,132.0 mm), reflecting the exceptional evaporative demand of tropical and subtropical species cultivated in Iran's arid regions. Although the average WRa of HWC horticulture crops (838.1 mm) was lower than that of HWC field crops (1,086.2 mm), the greater number of HWC horticultural species resulted in a cumulative WRa of 36,877.9 (mm, accounting for 72.3% of the total water use within the HWC category and representing the single largest contributor to agricultural water consumption in Iran. Overall, HWC crops (44 of 83 studied) accounted for 80.3% of total agriculture water use. These findings underscore that reforming horticultural cropping patterns, particularly by restricting tropical and subtropical species with high evaporative demand and promoting low-WRa alternatives, is essential for sustainable water resource management in Iran's water-stressed agricultural sector.

Key words: Horticultural crops; Crop water requirement; Irrigation management; Iran agriculture; Water consumption index

Water scarcity represents a critical global challenge, particularly in arid and semi-arid regions, directly impacting agricultural sustainability and food security worldwide (Khorsandi *et al*., 2023). Agriculture is the predominant consumer of freshwater resources globally, making the efficient management of water in this sector essential to meet the increasing demand for food amidst diminishing water supplies (Khorsandi *et al*., 2023). The escalating pressure on natural resources, including water, necessitates the development of innovative strategies to decrease water consumption in agriculture (Preite *et al*., 2023). Global spatially explicit crop water consumption data show an overall increase of 9% for 46 agricultural crops from 2010 to 2020, with observed increases in cropland area and higher crop water consumption putting additional pressure on limited water resources (Chukalla *et al*., 2025). Iran, characterized by its arid and semi-arid climate, faces severe water limitations that threaten the sustainability of its agricultural systems (Khorsandi *et al*., 2023). The country's agricultural sector heavily relies on internal water resources, leading to substantial impacts on both renewable and non-renewable water availability, particularly groundwater (Khorsandi *et al*., 2023). Iran's focus on food self-sufficiency has historically led to an emphasis on increasing water volumes for irrigation with little attention to water use efficiency (Karandish and Hoekstra, 2017). This approach, coupled with highly subsidized water and energy, has contributed to significant groundwater table decline across the country, underscoring dysfunctional feedback relations between agricultural water and energy pricing and groundwater withdrawal in an inefficient agronomic sector (Mirzaei *et al*., 2019). Groundwater comprises up to 83% of total blue water consumption for irrigated crops in Iran, with the highest share observed in arid areas and in cereals (Karandish *et al*., 2018).

Under such conditions, accurately understanding the actual water consumption (WRa) indicator of agricultural and horticultural products is essential for improving water-use efficiency, ensuring the sustainable management of water resources (Ebrahimipak *et al*., 2026; Khorsandi *et al*., 2023). There are significant differences in the amount of virtual water required for the production of various crops. For instance, pistachios (6,327.7 L kg^{-1}) and sesame (4,157.4 L kg^{-1}) have particularly high

Corresponding author : azadehsedaghat65@gmail.com

virtual water contents, whereas as citrus fruits, tomatoes, and cucumbers are recognized as low water- consuming crops (Ebrahimipak and Sedaghat, 2025). These differences highlight the necessity of optimizing cropping patterns and improving irrigation management practices (Ebrahimipak and Sedaghat, 2025). The Water Consumption Indicator has also been introduced as one of the key indicators within the Water-Energy-Food Nexus Index (WEFNI) framework for optimizing agricultural systems (Khajavigodellou *et al.*, 2026). To mitigate these challenges, improving water-use efficiency is an urgent task, especially in arid and semi-arid areas with fragile ecosystems and severe water shortages. A fundamental step in this process involves accurately determining the actual water consumption index of various agricultural and horticultural crops. This index is primarily quantified through measurements of crop evapotranspiration (ETc) and use of crop coefficients (Kc), which relate crop water use to a reference evapotranspiration (ETo) (Allen *et al.*, 1998). Precise estimation of ETc is crucial for optimizing crop water uses, particularly in the context of agriculture and horticultural production (Bijlwan *et al.*, 2024).

Numerous studies globally have focused on determining these critical parameters for various crops under diverse climatic conditions. For instance, in semi-arid regions of Ethiopia, research using lysimeters determined the seasonal actual crop evapotranspiration (ETc) for wheat to be 427.28 mm, with corresponding crop coefficient (Kc) values of 0.43 (initial), 0.93 (mid-season), and 0.30 (end growth stage) (Bayisa *et al.*, 2024). Similarly, for sorghum in Ethiopia, the average seasonal ETc was found to be 368.07 mm, with Kc values of 0.55 (initial), 1.15 (mid), and 0.59 (end-season) (Negash *et al.*, 2023). Maize in the same region exhibited an average seasonal ETc of 507.4 mm, with Kc values of 0.55 (initial), 1.19 (mid), and 0.56 (end seasons) (Negash *et al.*, 2024). For black beans in a subtropical region, the complete growing cycle ETc was 458.31 mm, with Kc values of 0.51 for the initial stage, 0.88 for vegetative, 1.20 for flowering, and 0.85 for maturity (Gil-Marín *et al.*, 2025). Horticultural crops have also been extensively studied; for example, onion in semi-arid Ethiopia showed a pooled seasonal ETc of 460.27 mm, with Kc values of 0.68 (initial), 0.89 (developmental), 1.03 (mid), and 0.86 (late-season) (Kebede *et al.*, 2025). In California's Central Valley, agricultural water use varied significantly, with rice showing an average of 1,110 ± 85 mm yr−1 and pistachio 592 ± 352 (mm yr^{-1}) (Wong *et al.*, 2021). A comprehensive study across the United States quantified monthly crop water consumption for 30 widely irrigated crops, revealing an average annual total crop water consumption of 154.2 km^3, with corn and alfalfa identified as significant consumers (Lamsal and Marston, 2025).

Distinguishing between high- and low-water-consuming crops is crucial for developing sustainable agricultural practices in water-stressed regions. This classification is often based on crop's water use efficiency (WUE), defined as the ratio between marketable yield and seasonal actual evapotranspiration (Katerji and Mastrorilli, 2014). Factors influencing WUE variability include agro-techniques, crop species and varieties, and environmental conditions (Katerji and Mastrorilli, 2014). For instance, a study in the Heihe River Basin, China, classified crops into high-water-consuming and low-water-consuming based on their average water consumption per hectare, demonstrating that policies like tiered water pricing can significantly reduce the proportion of high-water-consuming crops planted (Li *et al.*, 2023). Research indicates that switching to lower water intensity crops can reduce consumption by up to 93%, though this may require adopting less common crop types (Boser *et al.*, 2024). Water productivity in irrigated agriculture varies widely, with horticultural products often exhibiting higher economic water productivity compared to field crops due to their higher market value (Fereres *et al.*, 2003). To cope with scarce supplies, deficit irrigation, defined as the application of water below full crop-water requirements, is an important tool to reduce irrigation water use and improve water productivity (Fereres and Soriano, 2006). Understanding these specific water consumption values and their variations is crucial for optimizing irrigation scheduling and overall water resource management.

Therefore, this study aims to investigate the WRa index horticultural and field crops in Iran. By systematically analyzing the water requirements of various crops through their evapotranspiration and crop coefficients, this research seeks to distinguish between high- and low-water-consuming species based on their direct water consumption and water use efficiency. The findings are intended to provide critical insights for optimizing crop selection, improving irrigation management practices, and informing agricultural policies that promote water conservation and enhance food security. This comprehensive assessment will contribute to the development of more resilient and water-efficient agricultural systems in the face of increasing water scarcity.

MATERIALS AND METHODS

Study area and data

Iran covering about 1,648,195 km^2, and is located between 25°03′–39°47′ N latitude and 44°14′–63°20′ E longitude, bordered by the Persian Gulf, the Gulf of Oman, and the Caspian Sea. The country is largely mountainous, with the Alborz and Zagros ranges strongly influencing its climate.Northern and western regions experience semi-humid to Mediterranean conditions, while the central plateau is mainly arid to semi-arid. Mean annual temperatures range from 22 to 26 °C and may reach up to 45 °C in summer. Annual precipitation averages around 240 mm, but varies widely from about 1,800 mm along the Caspian coast to nearly 100 mm in central deserts. About 53% of Iran is mountainous, and 47% consists of plains. This study utilized data from the NIAZAB System (Soil and Water Research Institute of Iran (http://niwr.ir)) to calculate the virtual water index for 83 field and horticultural crops across three time intervals: 10-year, 5-year, and the 2022-2023 crop year. After examining the extracted data, it was found that the data for 10-year period (2013-2023) had more stable conditions, so the 10-year period was selected.

Description of NIAZAB System

The NIAZAB system is an integrated modeling platform designed to estimate crop water requirements, irrigation demand, and scheduling at regional and county levels. It operates based on a comprehensive national database that combines hydrological, soil, and crop-related information. The system offers standardized workflows, user-friendly functionality, and the capability to locally adjust key parameters. Its database includes daily weather observations, phenological data for more than 69,000 geo-referenced crop locations, over 300 crop types, cultivated land information, irrigation efficiencies, soil properties, and recorded crop yields. The computational framework of NIAZAB is built on widely accepted hydrological and agronomic methods, including the Penman–Monteith approach for reference evapotranspiration, crop coefficient techniques, estimation of standard and actual water consumes, effective rainfall, and crop water–yield relationships. These modules are linked with spatial datasets to estimate both irrigation demand and actual water consumption at daily and 10-day time scales for each crop. By combining advanced modeling tools with extensive spatial and climatic datasets, the system provides reliable and up-to-date estimations of irrigation indicators, thereby supporting efficient and sustainable water management in the field sector.

High- and low- water consuming crops

The process of identifying high water-consuming and low water-consuming agricultural crops was carried out through a multi-stage approach. In the first stage, the water requirement, irrigation water consuming, and actual water consumption of selected field and horticultural crops were estimated using a water requirement system based on climatic data, the physical and chemical properties of soil, and phenological stages of plants. In the second stage, crops with comparative advantage and export potential were identified and prioritized using official foreign trade statistics. Subsequently, results of water requirement assessment were integrated with the list of export-oriented crops to identify those that, despite having export potential, exhibit high water consumption and are therefore in conflict with optimal cropping patterns. The indices used as the basis for classifying crops into high water-consuming and low water-consuming groups are as follows:

Net crop water requirement (ETc): The ETc refers to the amount of water required by plants under standard conditions, without any limiting environmental factors affecting plant growth (Eq. 1). These conditions include the absence of plant diseases, adequate nutrient and fertilizer supply, large-scale cultivation with optimal soil moisture, and no water stress. Under such conditions, maximum crop yield is achieved in accordance with the climatic characteristics of the region.

$$ET_c = K_c \times] \qquad \text{Eq. 1}$$

where K_c is the crop coefficient and ET_0 is the reference evapotranspiration (mm day^{-1}) (Allan *et al.*, 1998). In CROPWAT 8.0, ET_0 was calculated using the FAO Penman–Monteith equation (Eq. 2). Meteorological input data, including mean wind speed, daily sunshine hours, minimum relative humidity, and average minimum and maximum air temperatures, were collected from 466 meteorological stations across the study area. Additionally, data on wheat production and cultivated area were obtained from the Agricultural Jihad Organization and the provincial statistical yearbooks.

$$ET_0 = \frac{0.408D(R_n - G) + \tilde{a}(\frac{900}{T + 273})U_2(e_s - e_a)}{D + \tilde{a}(1 + 0.34U_2)} \qquad \text{Eq. 2}$$

where Rn is the net radiation (MJ m^{-2} d^{-1}); G is the soil heat flux (MJ m^{-2} d^{-1}); T is the mean daily air temperature at 2 m elevation (°C); U_2 is the wind speed at 2 m elevation (m s^{-1}); es is the saturated water vapor pressure (kPa); ea is the actual water vapor pressure (kPa); es-ea is the water vapor pressure deficit at the reference height (kPa); Δ is the slope of the saturated water vapor pressure curve (kPa°C^{-1}); and γ is the psychrometric constant (kPa°C^{-1}).

Net irrigation water requirement (IRa): The net irrigation water requirement (IRa) is obtained as the difference between standard evapotranspiration and effective precipitation (Eq. 3)

$$IRa = ETc - Pe \quad \text{Eq. 3}$$

Pe: Effective precipitation refers to the portion of rainfall that reaches the ground surface and is stored within the plant root zone.

Actual water consumption (WRa): Actual water consumption is calculated by dividing the standard irrigation water requirement by the application efficiency (Es) (Eq. 4).

Table 1: WRa index of high water-consuming crops

Crop	Scientific name	WRa (mm)	Crops	Scientific name	WRa (mm)	Crops	Scientific name	WRa (mm)
			Horticulture crops			Field Crops		
Papaya	*Carica papaya*	1,387.6	Plum	*Prunus domestica*	750.3	Rattan sugarcane	*Saccharum officinarum*	3,046.8
Date palm	*Phoenix dactylifera*	1,286.4	Grape	*Vitis vinifera*	733.2	Alfalfa	*Medicago sativa*	1,603.9
Banana	*Musa acuminata*	1,217.0	Peach	*Prunus persica*	731.1	Paddy rice	*Oryza sativa*	1,249.0
Sapodilla	*Manilkara zapota*	1,132.0	Almond	*Prunus dulcis*	730.5	Spring Sugar Beet	*Beta vulgaris*	1,138.8
Guava	*Psidium guajava*	1,108.0	Jujube	*Ziziphus spina-christi*	726.2	Potato	*Solanum tuberosum*	1,130.6
Coconut	*Cocos nucifera*	1,063.9	Strawberry	*Fragaria × ananassa*	713.0	Onion	*Allium cepa*	1,047.9
Greengage plum	*Prunus domestica subsp. italica*	1,021.1	Fig	*Ficus carica*	705.5	Tomato	*Solanum lycopersicum*	1,036.5
Damask rose	*Rosa damascena*	967.0	Persimmon	*Diospyros kaki*	705.3	Clover	*Trifolium*	824.3
Cherry	*Prunus avium*	964.1	Mulberry	*Morus alba*	697.3	Cotton	*Gossypium hirsutum*	786.2
Apricot	*Prunus armeniaca*	941.3	Lime	*Citrus aurantiifolia*	689.5	Forage Maize	*Zea mays*	751.9
Peach	*Prunus persica*	916.7	Hazelnut	*Corylus avellana*	679.7	Grain Maize	*Zea mays*	747.2
Apple	*Malus domestica*	885.3	Pistachio	*Pistacia vera*	679.1	Tea	*Camellia sinensis*	734.1
Pear	*Pyrus communis*	874.7	Medlar	*Mespilus germanica*	670.9	Squash	*Cucurbita pepo*	720.9
Pomegranate	*Punica granatum*	871.4	Grapefruit	*Citrus × paradisi*	670.0	Bean	*Phaseolus vulgaris*	651.5
Walnut	*Juglans regia*	863.9	Orange	*Citrus sinensis*	670.0	Sesame	*Sesamum indicum*	639.8
Quince	*Cydonia oblonga*	844.2	Jujube	*Ziziphus jujuba*	659.8	Eggplant	*Solanum melongena*	621.5
Nectarine	*Prunus persica var. nucipersica*	828.4	Sweet Lime	*Citrus limetta*	641.3	Sunflower	*Helianthus annuus*	612.0
Sour cherry	*Prunus cerasus*	821.4	Raspberry	*Rubus idaeus*	609.4	-	-	-
Peach	*Prunus persica*	819.9	-	-	-	-	-	-
Mandarin	*Citrus reticulata*	806.0	-	-	-	-	-	-
Mango	*Mangifera indica*	799.7	-	-	-	-	-	-
Olive	*Olea europaea*	774.0	-	-	-	-	-	-
Maximum		1387.6				Maximum		3046.8
Minimum		609.4				Minimum		612.0
Average		841.4				Average		1020.2
Total Horticultural		33656.1				Total Field		17342.9
Total (Horticultural and Field Crops)				50999				

Table 2. WRa index of low water-consuming crops

Crops	Scientific name	WRa(mm)	Crop	Scientific name	WRa(mm)	Crops	Scientific name	WRa(mm)
Horticulture crops			Field Crops					
Barberry	*Berberis vulgaris*	556.5	Tobacco	*Tobacco*	556.5	Turnip	*Brassica rapa subsp. rapa*	419.0
Cornelian cherry	*Cornus mas*	496.0	Greenhouse cucumber	*Greenhouse cucumber*	553.2	Cucumber	*Cucumis sativus*	409.2
-	-	-	Chickpea	*Chickpea*	548.0	Cabbage	*Brassica oleracea var. capitata*	396.0
-	-	-	Pecan	*Pecan*	539.8	Barley	*Hordeum vulgare*	392.0
-	-	-	Hawthorn	*Hawthorn*	513.7	Saffron	*Crocus sativus*	379.0
-	-	-	Soybean	*Soybean*	506.2	Lettuce	*Lactuca sativa*	364.8
-	-	-	Melon	*Melon*	503.4	Canola	*Brassica napus*	338.0
-	-	-	Wheat	*Wheat*	483.0	Autumn sugar beet	*Beta vulgaris*	296.5
-	-	-	Watermelon	*Watermelon*	456.0	Kiwifruit	*Actinidia deliciosa*	269.6
-	-	-	Lentil	*Lentil*	452.0	Celery	*Apium graveolens*	269.5
-	-	-	Oleaster	*Oleaster*	445.0	Pepper	*Capsicum annuum*	263.0
-	-	-	Cantaloupe	*Cantaloupe*	436.9	Carrot	*Daucus carota subsp. sativus*	255.6
-	-	-	Sumac	*Sumac*	427.0	-	-	-
-	-	-	Cumin	*Cuminum cyminum*	420.0	-	-	-
Maximum		556.54		Maximum	556.50			
Minimum		495.98		Minimum	255.56			
Average		526.26		Average	423.57			
Total Horticulture		1,052.5		Total Field	11,436.3			
Total (Horticultural and field crops)					12488.85			

$$WRa=IRa/Es \qquad \text{Eq. 4}$$

In this study, the mean WRa index was employed as a threshold criterion to quantitatively and data-drivenly classify a wide range of field and horticultural crops into water-intensive and low water- consuming categories. Compared with the qualitative or arbitrary classifications adopted in many previous studies, this approach provides greater statistical robustness, as the 600 mm threshold was derived from the actual distribution of the dataset rather than from theoretical assumptions. Overall, 44 crops were classified as water-intensive, whereas 28 crops fell into the low water- consuming category. This asymmetric distribution indicates that a considerable proportion of Iran's agricultural crop portfolio imposes substantial pressure on water resources.

RESULTS AND DISCUSSION

Actual water consumption index (WRa)

The WRa, refers to the amount of water delivered to the field based on irrigation application efficiency and the actual irrigation water requirement of different crops (Ahmed *et al.*, 2024). Based on this index, the WRa of agricultural and horticultural crops was extracted in Tables 1 and 2.

The Wray index also incorporates the effects of irrigation method, irrigation efficiency, and water losses (Ahmed *et al.*, 2024), the mean value of this index was considered as the threshold distinguishing low water-consuming crops from high water-consuming crops (Ebrahimipak and Sedaghat, 2025). In this study, the average value of the WRa index was 600 mm. Therefore, crops with WRa greater than 600 mm are classified as high water-consuming crops, whereas crops with actual water consumption less than 600 mm are classified as low water-consuming crops.

Within the water-intensive category (Table 1), the horticultural subgroup dominated the upper end of the WRa spectrum, with tropical and subtropical species recording the highest values. Papaya (*Carica papaya*; 1,387.6 mm), date palm (*Phoenix dactylifera*; 1,286.4 mm), banana (*Musa acuminata*; 1,217.0 mm), sapodilla (*Manilkara zapota*; 1,132.0 mm), guava (*Psidium guajava*; 1,108.0 mm), coconut (*Cocos nucifera*; 1,063.9 mm), and greengage plum (*Prunus domestica subsp. italica*; 1,021.1 mm) were the most water-intensive horticultural crops, reflecting the high evaporative demand and year-round growing cycles characteristic of these species in Iran's southern and coastal provinces. Although sugarcane (*Saccharum officinarum*; 3,046.8 mm) recorded the single highest WRa among all crops, the cumulative WRa of water-intensive horticultural crops (33656.1 mm) far exceeded that of water-intensive field crops (17342.9 mm), confirming that the horticultural sector as a whole represents the dominant driver of agricultural water consumption in Iran.

Among water-intensive horticulture crops (Table 1), papaya (*Carica papaya*; 1,387.6 mm) and date palm (*Phoenix dactylifera*; 1,286.4 mm) ranked highest in terms of WRa. Both crops are tropical or subtropical species cultivated in regions characterized by extremely high atmospheric evaporative demand. In the same horticultural spectrum, crops such as banana (*Musa acuminata*; 1,217 mm) and Sapodilla (*Manilkara zapota;* 1,132.0 mm) also exhibited remarkably high WRa values. This finding is particularly concerning for rice cultivation, which has expanded in provinces such as Gilan and Mazandaran, where water resources have experienced increasing stress in recent years.

A comparison of the mean values of the two water-intensive subgroups reveals an important pattern. The average WRa of water-intensive field crops (1,086.2 mm) was substantially higher than that of water-intensive horticultural crops (841.4 mm), indicating that, on average, each water-intensive field crop consumes approximately 29.6% more water than its horticultural counterpart. Nevertheless, because the number of water-intensive horticultural crops considerably exceeds that of field crops, the cumulative WRa of the horticulture subgroup (33656.1 mm) accounts for nearly 72.3% of the total WRa within this category. This highlights the dominant contribution of the horticulture sector to agricultural water consumption in Iran. Crops with WRa values ranging between 600 and 750 mm, including raspberry (*Rubus idaeus;* 609.4 mm), Sweet lime (*Citrus limetta*; 641.3 mm), and jujube (*Ziziphus jujuba*; 659.8 mm), constitute a highly important transitional group. Although these crops were classified as water-intensive based on the selected threshold, from a management perspective they possess the greatest potential for shifting into the low water- consuming category through the adoption of advanced irrigation technologies, such as drip irrigation, regulated deficit irrigation, and precision irrigation management. Consequently, prioritizing this transitional group in extension and research programmes could yield the most immediate and effective reductions in agricultural water consumption in the short term.

The low water-consuming group exhibits a markedly different and statistically more compact structure compared with water-intensive group (Table 2). The WRa range within this category extends from 255.6 (mm) for carrot (*Daucus carota subsp. sativus*) to 556.5 (mm) for tobacco (*Tobacco*) and barberry (*Berberis vulgaris*), representing a spread of approximately 301 mm. In contrast to the more than 2,437 mm range observed in the water-intensive group, this narrower distribution indicates a substantially greater degree of homogeneity and clustering among low water-consuming crops.

The most significant finding in this group is presence of strategic cereal and oilseed crops. Wheat (*Wheat*), with a WRa of 483 (mm), barley (*Hordeum vulgare*) with 392 (mm), and canola (*Brassica napus*) with 338 (mm), are all key components of the country's food security system and were classified within low water- consuming category. This finding is particularly important because it suggests that food security and water security are not necessarily conflicting objectives; rather, they can be aligned through the promotion of crops that simultaneously exhibit strategic agricultural value and relatively low water requirements. Therefore, expanding the cultivation of these crops in arid and semi-arid regions appears justifiable from a water resource management perspective.

Within the low water- consuming horticultural subgroup (Table 2), the presence of barberry (*Berberis vulgaris*; 556.5 mm) and kiwifruit (*Actinidia deliciosa*; 269.6 mm) at the two extremes of the spectrum is particularly noteworthy. Barberry, a native crop of the Khorasan region cultivated under semi-arid conditions, exhibited a relatively moderate WRa within the low water- consuming category. In contrast, kiwifruit (*Actinidia deliciosa*), which is often perceived as a water-intensive crop, recorded a WRa of only 269.6 mm, placing it among the lowest values within this group. These finding challenges conventional assumptions regarding the water requirements of kiwifruit (*Actinidia deliciosa*) cultivation and may open new avenues for research on optimizing horticultural roduction under water-limited conditions. Furthermore, the overwhelming dominance of field crops within this category, accounting for 91.6% of the total WRa of low water- consuming crops, clearly indicates that Iran's field crop sector is substantially better aligned with water-scarcity conditions than the horticulture sector. This distinction highlights the comparatively greater adaptability of field crop production systems to arid and semi-arid environments.

The findings of this study showed substantial agreement with previous research. Based on the available literature, actual water consumption in horticultural crops varies considerably depending on crop type and environmental conditions. For instance, Ichwan et al. (2022) reported that pepper plants consumed approximately 151 (mL) of water per day under field capacity (FC) conditions, while irrigation at 50% of field capacity was found to be unsuitable due to its adverse effects on plant performance. Similarly, Zamani et al. (2024), in a study of horticultural crops in Iran, identified walnut as having the highest water scarcity footprint, reaching 2,652.78 (m^3 t^{-1} (, indicating substantial water requirements and significant environmental impacts associated with its production. Keyser-Gibson et al. (2025) investigated ornamental species, including Cercis occidentalis and Physocarpus opulifolius, and demonstrated that irrigation volumes could be significantly reduced without negatively affecting plant growth or overall performance. These findings highlight the potential for improving water-use efficiency through optimized irrigation management. Collectively, the available evidence emphasizes the critical importance of adopting crop-specific water management strategies to improve water productivity and support long-term agricultural sustainability.

Among horticultural crops, pistachio also exhibited a relatively high WRa value (679.1 mm).

This finding is consistent with the results reported by Ebrahimipak and Sedaghat (2025), who identified pistachio as one of the horticulture crops with the highest virtual water consumption, estimated at 6,327.7 (L kg^{-1}). Therefore, the expansion of pistachio (*Pistacia vera*) cultivation in regions facing water scarcity should be accompanied by more precise and sustainable water resource management practices. The mean WRa of water-intensive crops is approximately 2.1 times greater than that of low water- consuming crops (Fig 1). Moreover, the total cumulative WRa of water-intensive group reached 50,999 mm, compared with 12,488.85 mm for the low water- consuming group, representing a ratio of more than 4:1. This both horticultural and field crops, account for nearly 80.3% of total irrigation water consumption, whereas low water- consuming crops contribute only 19.7%. Altogether, the combined water consumption of both groups amounted to 63,485.85 (mm) (Fig 2). This pronounced asymmetry indicates that even a limited reduction in the cultivation share of water-intensive crops could produce a disproportionately large decrease in total agricultural water consumption, compared with merely expanding the cultivation of low water- consuming crops. In other words, the optimal strategy is not simply the promotion of low water- consuming crops, but rather a combined approach involving the targeted restriction of the most water-intensive crops, particularly sugarcane (*Saccharum officinarum*) and alfalfa (*Medicago sativa*), alongside the gradual replacement of transitional crops through cropping pattern reform and improvements in irrigation efficiency. Such a dual strategy could provide the greatest effectiveness in alleviating pressure on both renewable and non-renewable water resources, while simultaneously preserving crop diversity and the economic value of the field sector.

The high water-consuming horticultural crops have substantially greater water consumption, more than twice that of high water-consuming field crops (Fig. 2). In contrast, low water-consuming field crops exhibit higher water consumption than low water-consuming horticultural crops. Overall, high water-consuming horticultural crops account for the largest share of the total water use. Thus, a highly distinct pattern was observed between high water-consuming and low water-consuming crops in both horticultural and field crop groups. The WRa index, as an indicator of real water use, revealed considerable differences among these groups, reflecting the varying levels of pressure imposed on water resources under different cropping systems.

In the horticulture sector, the total WRa index for high water-consuming crops was reported as 33656.1 (mm), whereas the corresponding value for low water-consuming crops was only 17342.9 (mm). This substantial difference indicates that high water-consuming horticultural crops consume approximately 2.6 times more water than low water-consuming orchards. Such variation is mainly attributed to high

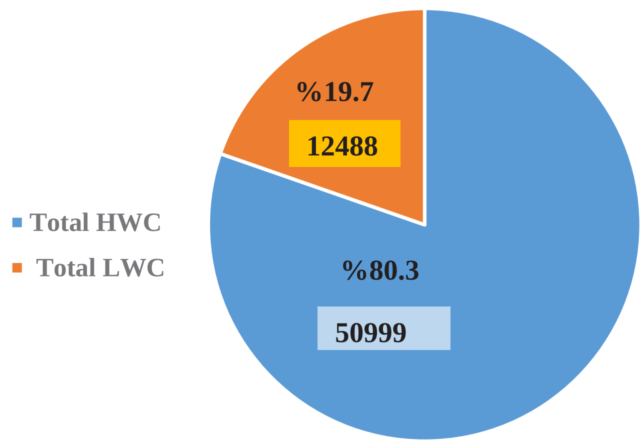

Fig. 1. Comparison of WRa between high water-consuming (HWC) and low water-consuming (LWC) crops

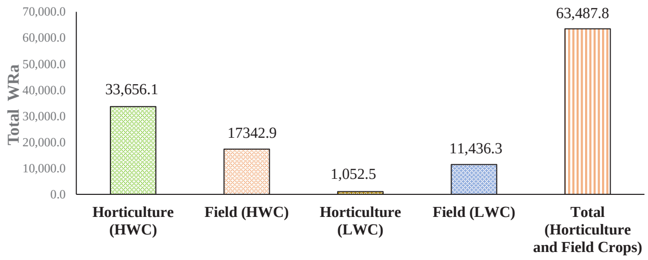

Fig. 2. Total WRa index of high and low water-consuming field and horticulture crops

water requirements of date palm (*Phoenix dactylifera*), papaya (*Carica papaya*), rice (*Oryza sativa*), and banana (*Musa acuminata*), which exhibited the highest WRa values (Table 1). In contrast, citrus, sesame (*Sesamum indicum*), sunflower (*Helianthus annuus*), and raspberry (*Rubus idaeus*) were categorized as low water-consuming crops (Table 2) and demonstrated significantly lower water demands. These findings indicate that the composition of horticultural cropping patterns has a direct impact on water withdrawal, replacing high water-consuming crops with low water-consuming species could play a significant role in sustainable water resource management. A similar trend was observed in field crops; however, magnitude of difference was even greater. The total WRa value for high water-consuming field crops was 11,436.3 (mm), compared with only 1,052.5 (mm) for low water-consuming field crops. In other words, high water-consuming field crops consume more than ten times the amount of water used by the low water-consuming group. This considerable gap highlights the high sensitivity of field sector to crop selection. Crops such as sugarcane (*Saccharum officinarum*), alfalfa (*Medicago sativa*), sugar beet (*Beta vulgaris*), and potato (*Solanum tuberosum*) exhibited the highest WRa values and therefore contributed most significantly to increased WRa, whereas low water-consuming crops such as canola (*Brassica napus*), lettuce (*Lactuca sativa*), celery (*Apium graveolens*), and carrot (*Daucus carota subsp. sativus*) required substantially less water. Overall, total WRa index for high water-consuming crops was markedly higher than that of low water-consuming crops, indicating that nearly 80% of total WRa is associated with high water-consuming crops (Fig. 1). This finding suggests that the current cropping pattern is highly dependent on crops with high water requirements. Under conditions of water scarcity and increasing pressure on water resources, maintaining such a pattern may seriously threaten the sustainability of the field sector.

The results of this study suggest that revising cropping patterns and promoting the cultivation of low water-consuming crops could be among the most effective strategies for reducing pressure on water resources. Furthermore, substantial differences observed between crop groups indicate that agricultural policies should be developed based on water productivity and WRa indices rather than solely on production performance. In practice, shifting toward crops with lower WRa values could help maintain agricultural production while simultaneously enhancing the resilience of agricultural systems to drought and climate change.

The findings of the present study WRa index are consistent with numerous studies reporting high water consumption in traditional horticultural and field crops, thereby supporting the validity of the graphical results. The HWC account for a substantially larger share of actual water consumption compared with LWC, such that total WRa in HWC group is considerably higher than that of LWC group (Fig. 2). This marked difference indicates that the current cropping pattern may impose significant pressure on water resources. Bekele (2025) emphasized that accurate estimation of crop water requirements is one of the fundamental pillars of sustainable water resource management and the design of optimal irrigation patterns. Accordingly, WRa index can serve as an effective tool for identifying crops with high water requirements and evaluating the sustainability of water use in field sector. Katerji and Mastrorilli (2014) stated that indices related to water use efficiency play a critical role in analyzing the performance of agricultural systems and optimizing water consumption, which is in agreement with the substantial differences observed between HWC and LWC crops in the present study.

The cropping pattern composition can directly contribute to reducing water consumption. Zou *et al.* (2018) reported that reducing the cultivated area of water-intensive crops and reforming cropping patterns in arid regions of China significantly decreased irrigation water demand. Likewise, Hao *et al.* (2018) demonstrated that optimizing cropping patterns based on water productivity can significantly reduce agricultural water consumption while maintaining economic profitability. Daccache *et al.* (2016) reported that replacing part of the high water-consuming crops with low water- consuming crops in the Mediterranean region resulted in the conservation of millions of cubic meters of water. Therefore, these findings suggest that incorporating the WRa index into cropping pattern planning can serve as an effective strategy for reducing pressure on water resources, improving water-use efficiency, and promoting sustainable agriculture, particularly in regions experiencing water scarcity and drought stress.

The study of the WRa index in plants is an important field within plant ecology and agricultural sciences that examines how different plant species utilize water resources. Its importance has increased significantly due to the intensifying global water scarcity caused by climate change, population growth, and rising agricultural demands (Brendel, 2021). Research in this field has evolved from early philosophical observations to advanced scientific investigations during the nineteenth and twentieth centuries, focusing on the complex physiological responses of plants to environmental conditions. Recent technological advances, including smart irrigation systems and artificial intelligence, have enabled real-time monitoring and optimization of water consumption, thereby enhancing agriculture resilience to climate change (Hatfield and Dold, 2019). Nevertheless, several challenges remain, including the lack of accurate datasets, environmental variability, and the need for localized assessments to adapt findings to different ecological conditions (Tercek *et al.*, 2021). Overall, the study of plant water consumption indices not only improves our understanding of plant biology and ecology but also plays a critical role in the development of sustainable agricultural practices and policies aimed at conserving valuable water resources.

CONCLUSION

This study classified 83 field and horticulture crops in Iran into high and low water-consuming categories based on their actual water consumption (WRa) using a national dataset covering the period 2013–2023. The results revealed a pronounced imbalance in agricultural water use, with high water-consuming crops accounting for 80.3% of total WRa. Although several field crops, particularly sugarcane (*Saccharum officinarum*) and alfalfa (*Medicago sativa*), exhibited the highest individual WRa values, the horticultural sector emerged as the dominant contributor to agricultural water consumption because of the large number of water-intensive horticultural species. Among horticulture crops, papaya (*Carica papaya*), date palm (*Phoenix dactylifera*), banana (*Musa acuminata*), sapodilla (*Manilkara zapota*), and guava (*Psidium guajava*) showed the highest WRa values, reflecting the considerable water demand of tropical and subtropical species cultivated under Iran's arid and semi-arid conditions. Collectively, high water-consuming horticultural crops accounted for 72.3% of the total WRa within the high water-consuming category, highlighting the critical role of horticulture crop selection in national water-resource management. In contrast, crops such as kiwifruit (*Actinidia deliciosa*) and barberry (*Berberis vulgaris*) exhibited relatively low WRa values, indicating their potential as more water-efficient alternatives for future horticultural development.

The results also demonstrated that several strategic field crops, including wheat (*Triticum aestivum*), barley (*Hordeum vulgare*), and canola (*Brassica napus*), were classified within the low water-consuming category, suggesting that improvements in water security do not necessarily conflict with food-security objectives. Furthermore, crops with WRa values near the 600-mm threshold, including sesame (*Sesamum indicum*) and sunflower (*Helianthus annuus*), represent promising candidates for reducing agricultural water use through improved irrigation management and precision irrigation technologies. Overall, the findings indicate that sustainable agricultural water management in Iran should prioritize reforming horticulture cropping patterns while simultaneously improving irrigation efficiency in both horticulture and field crop systems. Restricting the expansion of highly water-intensive horticultural species, promoting low-WRa alternatives, and incorporating WRa-based criteria into agricultural planning can substantially reduce pressure on water resources and enhance the long-term sustainability of Iranian agriculture under increasing water scarcity and climate change.

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