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ORIGINAL PAPER

Economic analysis of water footprint for water management of rain-fed and irrigated almonds in Iran

Ommolbanin Bazrafshan[1] · Kambiz Vafaei[1] · Hadi Ramezani Etedali[2] · Hossein Zamani[3] · Masoumeh Hashemi[4]

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Abstract
Applying hydrological concepts, such as water footprint, economical water footprint, and virtual water trade is necassary to improve water resource management. This study considers the concepts of water footprint and economical water footprint to prioritize the cultivation of rain-fed and irrigated almonds in Iran during 2006–2016. The study results shows that the rain-fed average water footprint and economical water footprint are 9.2 m^3kg^{-1} and 2.88 m^3 per $, respectively, with 72% of the share being green water footprint, and 28% being grey. Irrigated almonds' water footprint and economical water footprint are 11.4 m^3kg^{-1} and 5.16 m^3 per $, with the share of green, blue, and grey water footprints being 19%, 71%, and 10%, respectively. The total Average water footprint (AWF) of almond production is 10167.3 MCM $year^{-1}$, 80% being irrigated and 20% being rain-fed. About 9343 MCM $year^{-1}$ of this amount is exported overseas as the virtual water trade. Increasing the yield of almonds in rainfed orchards improves the productivity of green water, and as a result, irrigated orchards will be reduced; therefore, the pressure on water resources will be reduced based on WF criteria. The results of this study demonstrate that due to water and soil limitations in Iran, the concepts of water footprint and economical water footprint provide useful information for the conservation and management of water resources in agriculture by combining local and regional data on water availability and scarcity.

Introduction

Almond (*Prunus dulcis*) is a versatile nut with high nutritional value, including fiber, protein, fat, and micro-nutrients (Chen et al. 2006). According to the FAO statistics (2017) and INC (2018), Iran, with the production of over 111845 tons of almonds per year, was ranked as the fourth biggest producer in the world after United States, Spain, and Australia. Iran was also ranked fourth in production of almond, with 6% of almond exports worldwide (MAJ 2018).

Iran has inherently limited water resources due to its arid and semi-arid climate. However, more than 90% of its water resources are used in agriculture, such that more than 388 aquifers in Iran are in a critical situation, and the production of many agricultural and horticultural products is facing severe challenges (Madani 2014).

Almond orchards, with an average cultivation area of 155 thousand hectares, contain 23% of dried fruit lands in Iran and, after pistachios, rank second among the nut crop exports. Furthermore, more than 51% of almond orchards are located in arid and semi-arid areas and are irrigated with groundwater (MAJ 2018).

Over the past decades, the agricultural production policy in Iran has been based on the self-sufficiency of strategic crops, such as wheat, barley, and corn (Maroufpoor et al. 2021). The water footprint (WF)/virtual water (VW) has been proposed as a solution for water management in many countries facing water scarcity (Garrido et al. 2010; Ngo et al. 2018; Zhang et al. 2018; Crovella et al. 2022). The concept of WF can be proposed as a helpful tool in calculating the amount of actual water consumed in a region, and if international exchanges of VW are considered, it will significantly help to make decisions about the export and import of goods.

✉ Ommolbanin Bazrafshan
O.bazrafshan@hormozgan.ac.ir

[1] Department of Natural Resources Engineering, University of Hormozgan, Bandar Abbas, Iran

[2] Department of Water Sciences and Engineering, Imam Khomeini International University (IKIU), Qazvin, Iran

[3] Department of Mathematics and Statistics, University of Hormozgan, Bandar Abbas, Iran

[4] Civil Engineering Department, Remote Sensing Research Center, Sharif University of Technology, Tehran, Iran

The WF is a new approach to evaluating the usage of water resources for agricultural production (Lamastra et al. 2014). Analysis of WF helps researchers determine water consumption situations and then estimates the imported/exported amounts of water. The VW concept is the water embedded in agricultural products through production and supply chain processes (Allan 1993). Virtual water trade (VWT) is a practical approach to overcoming the lack of water resources in countries that face water shortages. It can be an effective tool for water-scarce regions to alleviate their water scarcity problem by importing water-intensive crops rather than growing them domestically (Wahba et al. 2018).

The WF index measures the water volume that is used for producing goods or providing services directly or indirectly. The WF of agricultural products is defined as the sum of freshwater used in the production chain process (Morillo et al. 2015). The water resources are divided into blue and green in the hydrology cycle. The blue water contains the ground water resources and surface flow, while the green water is the stored moisture in the unsaturated zone utilized by plants (Wang et al., 2019). The green water sources is precipitation, while the blue water resources are aquifers, lakes and dams (Hoekstra and Hung 2003; Shtull-Trauring and Bernstein 2018). In this situation, the main source of rain-fed agriculture is green water, while the irrigated lands are fed by blue water. Grey water is defined as polluted water resulting from the production process and is usually used to dilute chemical fertilizers and pesticides (Obuobie et al. 2006).

Many researchers have applied the concepts of WF/VW in agriculture products. For instance, computing the WF of rice in the north of China, South Korea, and Italy (Xinchun et al. 2018; Yoo et al. 2014; Bocchiola 2015), maize in Italy (Nana et al. 2014; Bocchiola et al. 2013), olives in Spain (Salmoral et al. 2011), potatoes in Argentina (Rodriguez et al. 2015), wheat in China (Wang et al. 2015; Sun et al. 2012), cocoa in Colombia (Ortiz-Rodriguez et al. 2015), almonds in California, cereals in Iran (Ababaei and Ramezani Etedali 2017), saffron, tomatoes and citrus in Iran (Bazrafshan et al. 2019a, b; Bazrafshan and Gerkaninezhad Moshizi, 2018).

Fulton et al. (2019) considered the temporal analysis of WF and California's economic water footprint (WFE) for almond production. The results showed that the average WF and WF_E are 10.24 m^3/kg and 2.22 m^3/USD, respectively. In addition, their results demonstrated that almond production has the highest WF_E among berries and nuts.

Despite the growing enthusiasm for the development and use of WF/VW in the world, several researchers have raised significant concerns about its concept and its usefulness, both as a water management and policy tool, as it does not provide sufficient information on the cost of water, and as an indicator of economic and environmental impact (Novoa et al. 2019; Chenoweth et al. 2014; Wichelns 2011; Perry 2014).

This study applies the concepts of WF and economical WF for almond production in Iran. Although Iran is located in the mid-latitude belt of earth and is inherently faced with water shortage problems, it ranks high in several agricultural products, such as onions, cucumbers, date palms, saffron, plum oil, figs, walnuts, and almonds. It is important to note that water managers in Iran could pay attention to the management of the water consumption in the agricultural sector based on the economic benefit as well as their water footprints. Because attention to WF/VW is one way to minimize the gap between water supply and demand, countries with water shortage can reduce production or export of products with high WF/VW and compensate for this reduction by importing products from other countries.

The WF is defined as an index for the allocation of freshwater resources and is used to formulate strategies for the allocation of water resources in an area. A review of previous studies in Iran indicates that allocation methods did not follow a specific procedure and were based only on water supply and demand (i.e., Taghizadeh et al. (2013); Mohammadi et al. (2015); Hosseinzad et al. (2014). However, nowadays, allocation is based on food security, water resource management, water productivity (Mohammadrezapour et al. (2019); Chakraei et al. (2021); Mazraeh et al. (2022)). This method was also proposed worldwide by authors, such as Lu et al. (2022), Chouchane et al. (2020); Ye et al. (2018), and Avios et al. (2018).

The application of WF/VW in the allocation of water resources is a new approach that has recently been considered in Iran and proposed by several authors, such as Maroufpoor et al. (2021); Sedghamiz et al. (2018); Mojtabavi et al. (2018); Ramezani Etedali et al. (2019) Arefinia et al. (2022).

The Iranian government's policies have made farmers focus only on crop production, not water conservation. However, the market allocation should not affect water resources as an essential natural resource for agriculture. One of the approaches to reach these goals is to use the WF approach to allocate water resources at a regional scale.

The concept of WF/VW is currently considered one of the components of measuring water productivity in various study fields of the water industry. Applying this concept can be a valuable tool in water saving and water security based on Iran's specific political and climatic conditions to prioritize cultivation, choosing the best combination of cultivation, and relative self-sufficiency in the production of agricultural products. Special attention should be paid to the water footprint (physical and economic) and productivity

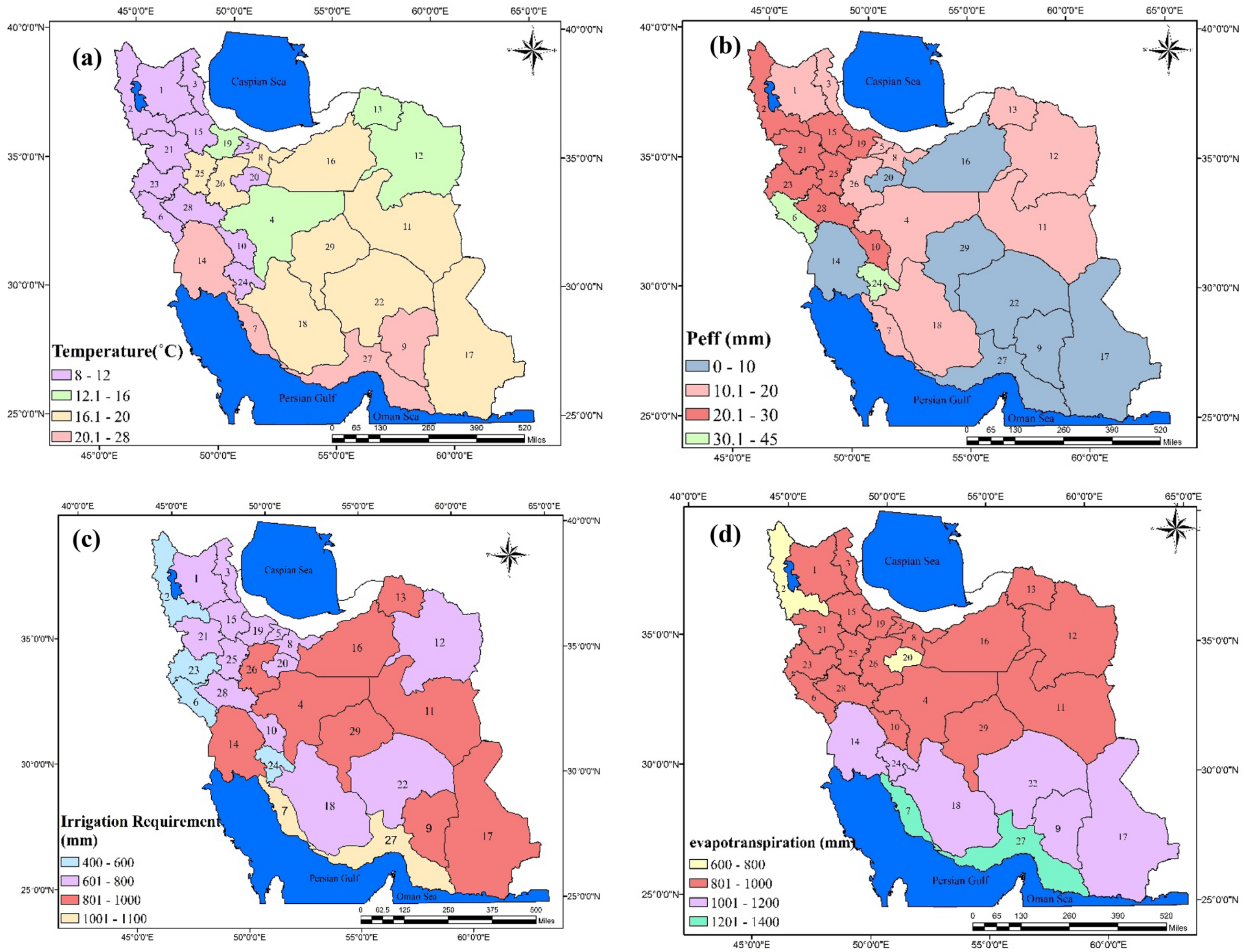

Fig. 1 Spatial distribution of weighted average temperature (**a**), effective rainfall (**b**), irrigation water requirement (**c**) and crop evapotranspiration (**d**) for almond producing provinces (the name of the provinces is represented in Table 1)

of agricultural and horticultural products to allocate water resources within the agricultural sector.

According to the literature reviews, several estimations exist for water footprint on a global (Mekonnen and Hoekstra 2011) and regional scale (Chouchane et al. 2015; Fulton et al. 2019) for almond products. As mentioned above, Iran is the fourth-largest producer of almonds, with most being exported overseas, and yet, the literature shows no study on WF and WF_E for irrigated and rain-fed almonds at the regional level for Iran (and prioritization.) The aims of this study are (1) to determine WF and WF_E of the rain-fed and irrigated almonds during 2006–2016, (2) to calculate WF components for exported products at the national and provincial level, (3) to estimate annual VW flows associated with almond trade, and (4) to prioritize the provinces that produce the rain-fed and irrigated almond—based on WF and WF_E.

Materials and methods

Data source

The data used in this research are divided into crop data and climatic data. The crop data includes cultivated area, yield per hectare, chemical fertilizer, irrigation efficiency, crop coefficient, planting calendar, and soil type which are collected from the Ministry of Agriculture Jihad organization (MAJ 2018). In addition, the climatic data are collected from IRIMO (2016) for each province during

Table 1 Information concerning almond production in Iran for the rain-fed and irrigated orchards during 2006–2016

Province	Code	Production (ton)			Share (%)		National share (%)		Fertilizer (kg/ha)		Yield (ton/ha)	
		Irrigated	Rain-fed	Total	Irrigated	Rain-fed	Irrigated	Rain-fed	Irrigated	Rain-fed	Irrigated	Rain-fed
Azerbaijan Shargi	1	6909	492	7401	93	7	7.14	1.52	53	45	1.2	0.5
Azerbaijan Gharbi	2	2959	198	3157	94	6	3.06	0.61	58	45	1.5	0.6
Ardabil	3	107	134	241	44	56	0.11	0.42	59	45	1.3	0.4
Isfahan	4	6886	339	7225	95	5	7.11	1.05	47	35	1.2	0.5
Alborz	5	336	5	341	99	1	0.35	0.02	55	40	1.6	0.5
Ilam	6	122	232	354	34	66	0.13	0.72	56	45	0.7	0.7
Boshehr	7	17	2	18	91	9	0.02	0.01	51	35	2.6	–
Tehran	8	518	–	518	100	–	0.54	–	51	45	3	–
South Kerman	9	193	–	193	100	–	0.20	–	53	35	1.6	–
Chaharmahal & Bakhtiari	10	14349	82	14430	99	1	14.82	0.25	54	45	1.7	0.5
Khorasan Jonoobi	11	5863	3521	9384	62	38	6.06	10.91	52	45	1.4	0.5
Khorasan Razavi	12	6556	5501	12058	54	46	6.77	17.05	55	45	0.8	0.3
Khorasan Shomali	13	1248	1550	2798	45	55	1.29	4.80	57	35	1.4	0.6
Khouzestan	14	102	91	193	53	47	0.11	0.28	53	35	2.5	1.8
Zanjan	15	1685	106	1791	94	6	1.74	0.33	57	35	1.5	0.5
Semnan	16	1308	9	1318	99	1	1.35	0.03	53	45	1.5	–
Sistan & Balochestan	17	237	–	237	100		0.24	–	51	35	1.9	0.1
Fars	18	12730	14471	27201	47	53	13.15	44.84	58	45	2	0.7
Qazvin	19	6291	2359	8650	73	27	6.50	7.31	57	35	1	0.4
Qom	20	798	2	799	100	0	0.82	0.01	54	45	1.1	0.1
Kurdistan	21	523	341	864	61	39	0.54	1.06	57	35	1.1	0.6
Kerman	22	6665	658	7323	91	9	6.89	2.04	55	45	1.1	0.3
Kermanshah	23	3362	585	3947	85	15	3.47	1.81	59	45	2.1	0.5
Kohgiluyeh & Boyer-Ahmad	24	692	205	897	77	23	0.71	0.64	60	45	1.2	0.8
Lorestan	25	2511	140	2651	95	5	2.59	0.43	60	45	1.2	0.3
Markazi	26	5277	124	5400	98	2	5.45	0.-38	54	45	1.1	0.4
Hormozgan	27	732	6	738	99	1	0.76	0.02	53	35	1.5	0.1
Hamedan	28	4288	1081	5369	80	20	4.43	3.35	57	45	1.4	0.5
Yazd	29	3528	38	3566	99	1	3.64	0.12	51	35	0.5	0.2
Total	–	96792	32272	129062	2361	539	100	99.6	1590	1190	42.7	12.4
Average	–	3337.7	1241.2	4450.4	81.4	20.7	3.4	4	54.8	41	1.5	0.5
Max	–		14349	27201	100	66	14.8	44.8	60	45	3	1.8
Min	–	17	2	18	34	0	0	0	47	35	0.5	0.1

Reference (MAJ 2018)

2006–2016. The climatic variables contain the average of 10-year precipitation (mm), relative humidity (%), sunshine hours (hr), maximum temperature (^{o}c), minimum temperature (^{o}c), and wind speed (km/day) for the given duration. Figure 1 and Table 1 provide some of this information.

Twenty-nine provinces in Iran produce the irrigated almond, and twenty-five of these provinces produce the rain-fed almond. The shares of irrigated and rain-fed almond orchards are 51% and 49%, respectively. The cultivated regions are in the semi-arid, arid, and Mediterranean climates. Among those provinces, Chaharmahal & Bakhtiari, with an annual rainfall average of 661 mm, and Yazd, 82 mm, have the greatest and the least precipitation, respectively (IRIMO 2018).

Methods

Computing water footprint components

In this study, we compute the green (WF_{Green}), blue (WF_{Blue}), and grey water footprints (WF_{Grey}) for almond products in Iran. The water footprints are calculated by applying Hoekstra and Chapagain's framework (2008) and Al-Muaini et al. (2019) from 2006 to 2016, since the water resources and agriculture are managed at the provincial level in Iran (MAJ 2018). This study was implemented at the provincial scale.

Climatic data, including precipitation, relative humidity, sunshine hours (minimum and maximum air temperature, and wind speed, were collected from the Meteorological Organization of Iran[1] (IRIMO 2018) during 2006–2016. The climatic data were used to calculate the effective precipitation (Peff), net irrigation requirement, and crop evapotranspiration.

The water requirement, irrigation requirement, and effective precipitation are computed using the CROPWAT model. In this regard, the crop evapotranspiration and water requirement are calculated by FAO–Penman–Monteith under the standard and non-standard conditions using the CROPWAT model (Allen et al. 1998). In addition, the data of the CROPWAT model are used for the gross irrigation requirements (GI_{Irr}). The net irrigation requirements (IR_{Irr}) were calculated by considering each province's gross irrigation requirements and irrigation efficiency (IEIrr). Then, the total net irrigation requirements (IR_{Irr}) was calculated as the difference between total actual crop evapotranspiration (ETc) and total effective precipitation (P_{eff}). After that, the green and blue crop water uses (CWU) and WF were estimated using the following equations:

$$CWU_{Blue,Irr} = IR_{Irr} = 10 \times IE_{Irr} \times GII_{rr} \quad (1)$$

$$CWU_{Green,Irr} = (P_{eff}) \times 10 = 10 \times (ETc - IR_{Irr}) \quad (2)$$

$$CWU_{Blue,RF} = 0 \quad (3)$$

$$CWU_{Green,RF} = 10 \times P_{eff} \quad (4)$$

$$WF_{Blue,Irr} = \frac{CWU_{Blue,Irr}}{Y} \quad (5)$$

$$WF_{Green,\,Irr} = \frac{CWU_{Green,Irr}}{Y} \quad (6)$$

$$WF_{Green,\,RF} = \frac{CWU_{Green,RF}}{Y_{RF}} \quad (7)$$

$$WF_{Grey,Irr} = \frac{\alpha_{Irr} \times NAR_{Irr}}{C_{Max} - C_{Nat}} \times \frac{1}{Y_{Irr}} \quad (8)$$

$$WF_{Grey,RF} = \frac{\alpha_{RF} \times NAR_{RF}}{C_{Max} - C_{Nat}} \times \frac{1}{Y_{RF}} \quad (9)$$

where Irr and RF refer to irrigated and rainfed conditions, respectively, and 10 is the conversion factor from mm to m^3/ha. The WF_{Green} WF_{Green}, WF_{Blue} WF_{Blue}, and WF_{grey} WF_{Grey} are water footprints in units of m^3 kg^{-1} (Bazrafshan et al. 2019a). The P_{eff} represents the sum of effective rainfall, which can be obtained using the USDA S.C. Method (Chapagain et al. 2006) during the growing season (mm), and Y crop yield in mature almonds (tone ha^{-1}). Since yields are different under irrigated and rainfed conditions, the WF components were calculated with the respective actual yields under each condition. All WF components were estimated for all the provinces. Irrigated and rainfed yields were obtained from the Ministry of Jihad (MAJ) for the period 2006–2016 at a provincial scale. α is the percentage of nitrogen fertilizer loss (α is considered 10% under irrigation and 5% under rainfed conditions (Chapagain et al. 2006; Ababaei and Ramezani Etedali 2017), NAR is the rate of used nitrogen fertilizer (kg ha^{-1}), C_{Max} is the critical concentration of nitrogen fertilizer (kg m^{-3}). C_{Nat} is the real nitrogen concentration in the receiving water (kg m^{-3}).

Through this study, the WF_{Gray} WF_{Grey} is computed only for nitrogen fertilizer, where the maximum nitrogen concentration based on the USEPA (USEPA 2017) in receiving standard water is 10 mg l^{-1}. In addition, the C_{Nat} is considered zero due to the lack of information about the real nitrogen concentration in receiving water (Chapagain et al. 2006). The green, blue, and gray WFCs of almond production (irrigated and rainfed) were estimated by taking each province's average WF (m3/kg)

[1] https://www.irimo.ir.

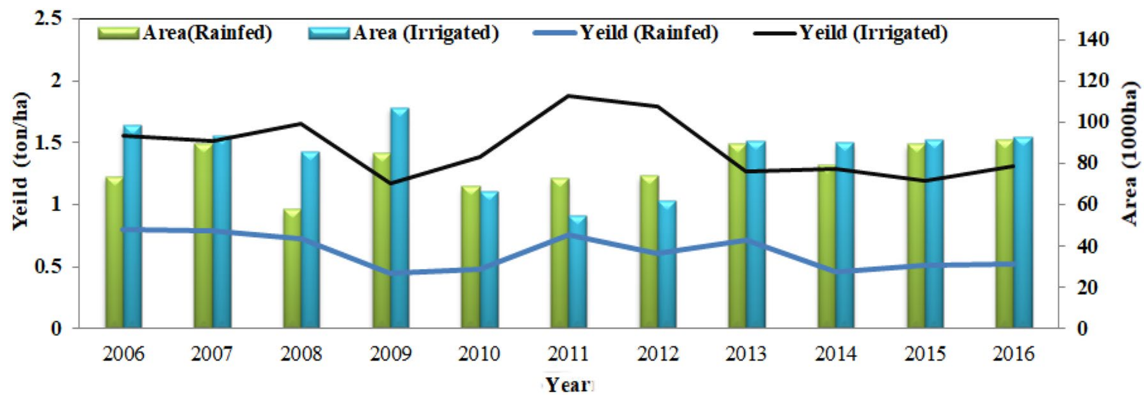

Fig. 2 Temporal variation of sown area and crop yield of rain-fed and irrigated almonds in Iran during 2006–2016

of the respective provinces. Finally, the national WF components were calculated by taking the weighted average of each component over all the provinces by the share of each province in the whole almond production of the combined provinces (Ababaei and Ramezani Etedali 2017), according to the data obtained from MAJ.

Once the provincial WF components are calculated for each selected province, the total volume of WF components in each province and national scale can be obtained as the weighted average of WFs under rainfed and irrigated almonds, as shown in Eqs. (10) and (11):

$$WFV_x = \sum_i WF_{i,x} \Pr od_{i,x} \quad \mathrm{i} = 1, \ldots, 29, \mathrm{x} = \text{ blue, green, grey} \tag{10}$$

$$AWF = \frac{\sum_i WFV_{i,x}}{\sum_i \Pr od_{i,x}} \tag{11}$$

Here i is the index of the province, x is WF components (blue, green, grey), $\Pr od_{i,x}$ is the amount of almonds that are produced in the ith province under rain-fed and irrigated conditions (kg), WFV_x is the total volume of each WF component (MCM), AWF is the national weighted average of each WF component under irrigated and rain-fed conditions (m^3 kg-1).

Calculation of economic water footprint

The economic WF (WF_E) can be calculated through Eqs. (12), (13), and (14):

$$WF_{E\,(Green)} = \frac{WF_{Green}}{NB} \tag{12}$$

$$WF_{E\,(Blue)} = \frac{WF_{Blue}}{NB} \tag{13}$$

$$WF_{E\,(Grey)} = \frac{WF_{Grey}}{NB} \tag{14}$$

where $WF_{E\ (Green)}$, $WF_{E(Blue)}$, and $WF_{E(Grey)}$ are the almond economic water footprint of green, blue, and grey (m^3 US\$$^{-3}$) in each province under irrigated and rain-fed conditions, and NB is the net benefit that on average is 3 dollars per one kilogram rainfed and 2.2 dollars per one kilogram irrigated almonds during the study period (MAJ 2018).

To obtain the same areas in terms of WF and WF_E indices, the provinces are clustered using the K-means clustering approach as one of the most popular and the simplest partitional algorithms (Jain 2010).

Results

The sown area, total production, and yield of almond production

The average almond orchard yield (kg ha-1) and area (ha) for the duration of 2006–2016 are displayed in Fig. 2 (MAJ 2018). The almond orchard area of irrigated (536.8 ha per year) and rainfed (1520 ha per year) has increased, while the yields have decreased. The crop yield of rain-fed almonds has decreased from 0.8 to 0.5 ton ha-1 (2.41 kg/ha per year), while this reduction is 1.7–1.31 ton ha-1 (27.7 kg/ha per year) for the irrigated almonds entire the 11-year period. According to the MAJ (2018) report, the most important reasons for decreasing trend of almond yield in the last two decades are frequent droughts, frosting and climate change in Iran.

The average cultivated almond area in rain-fed and irrigated orchards is 79,306 and 75,048 ha, respectively, with a production of 130,000 tons per year. More than 75% of these have been harvested from irrigated orchards (MAJ 2018). Fars and Khorasan Razavi provinces have

Table 2 WF components of rain-fed and irrigated almonds and WF_E in Iran

Province	WF(Rain-fed) (m^3/kg)			WF_E(Rain-fed) (m^3/\$)	WF(Irrigated) (m^3/kg)				WF_E(Irrigated) (m^3/\$)
	Green	Grey	Total		Green	Blue	Grey	Total	
Azerbaijan Shargi	9.3 (66%)	4.7 (34%)	14	4.38	5.4 (14%)	26.4 (69%)	6.4 (17%)	38.2	17.36
Azerbaijan Gharbi	9.7 (90%)	1.1 (10%)	10.7	3.34	3.3 (30%)	5.9 (54%)	1.7 (16%)	10.9	4.95
Ardabil	4.9 (83%)	1.0 (17%)	5.9	1.84	2.4 (24%)	6.8 (67%)	1 (10%)	10.2	4.64
Isfahan	4.6 (70%)	2.0 (30%)	6.6	2.06	1.2 (13%)	7.3 (82%)	0.4 (4%)	8.9	4.05
Alborz	2.7 (86%)	0.4 (14%)	3.1	0.97	1.1 (24%)	3.4 (74%)	0.1 (2%)	4.6	2.09
Ilam	4.8 (91%)	0.5 (9%)	5.3	1.66	7.2 (36%)	10.8 (53%)	2.2 (11%)	20.2	9.18
Boshehr	3.9 (32%)	8.2 (68%)	12	3.75	0.8 (12%)	5.6 (85%)	0.2 (3%)	6.6	3.00
Tehran	–	–	–	–	0.6 (19%)	2.5 (78%)	0.1 (3%)	3.2	1.45
South Kerman	–	–	–	–	0.9 (11%)	7.1 (87%)	0.2 (2%)	8.2	3.73
Chaharmahal & Bakhtiari	5.4 (79%)	1.4 (21%)	6.9	2.16	1.7 (27%)	4.4 (70%)	0.2 (3%)	6.3	2.86
Khorasan Jonoobi	2.4 (71%)	1.0 (29%)	3.4	1.06	0.9 (13%)	5.9 (83%)	0.3 (4%)	7.1	3.23
Khorasan Razavi	10.9 (56%)	8.4 (44%)	19.3	6.03	2.6 (18%)	10.3 (72%)	1.4 (10%)	14.3	6.50
Khorasan Shomali	9.2 (56%)	7.1 (44%)	16.3	5.09	2.5 (22%)	7.8 (69%)	1 (9%)	11.3	5.14
Khouzestan	0.5 (74%)	0.2 (26%)	0.7	0.22	0.4 (8%)	4.4 (90%)	0.1 (2%)	4.9	2.23
Zanjan	13.5 (87%)	2.1 (13%)	15.6	4.88	3.2 (25%)	7.8 (62%)	1.6 (13%)	12.6	5.73
Semnan	–	–	–	–	0.8 (12%)	5.7 (85%)	0.2 (3%)	6.7	3.05
Sistan & Balochestan	–	–	–	–	0.4 (6%)	5.8 (91%)	0.2 (3%)	6.4	2.91
Fars	3.4 (79%)	0.9 (21%)	4.3	1.34	1.1 (20%)	4.1 (76%)	0.2 (4%)	5.4	2.45
Qazvin	6.4 (84%)	1.3 (16%)	7.7	2.41	4.9 (23%)	13 (61%)	3.5 (16%)	21.4	9.73
Qom	–	–	–		1.1 (9%)	10.8 (84%)	1 (8%)	12.9	5.86
Kurdistan	6.4 (88%)	0.9 (12%)	7.3	2.28	3.2 (32%)	6 (60%)	0.8 (8%)	10	4.55
Kerman	5.4 (43%)	7.2 (57%)	12.6	3.94	1.4 (11%)	10.8 (83%)	0.8 (6%)	13	5.91
Kermanshah	9.8 (55%)	7.9 (45%)	17.6	5.50	1.6 (34%)	2.9 (62%)	0.2 (4%)	4.7	2.14
Kohgiluyeh & Boyer-Ahmad	7.2 (91%)	0.7 (9%)	7.9	2.47	5.7 (36%)	7.7 (49%)	2.3 (15%)	15.7	7.14
Lorestan	10.8 (82%)	2.4 (18%)	13.2	4.13	3 (34%)	5.3 (60%)	0.5 (6%)	8.8	4.00
Markazi	6.5 (74%)	2.2 (26%)	8.7	2.72	2.2 (24%)	6.4 (70%)	0.5 (5%)	9.1	4.14
Hormozgan	–	–	–		1.1 (9%)	10.7 (87%)	0.5 (4%)	12.3	5.59
Hamedan	7.7 (77%)	2.2 (23%)	9.9	3.09	2.3 (28%)	5.3 (65%)	0.6 (7%)	8.2	3.73
Yazd	1.2 (39%)	1.8 (61%)	2.9	0.91	1.1 (4%)	21.6 (81%)	4.1 (15%)	26.8	12.18
Average	9.3	4.7	9.2	2.88	2.2	8	1.1	11.4	5.16
Max	9.7	1.1	19.3	6.03	7.2	26.4	6.4	38.2	17.36
Min	4.9	1.0	0.7	0.22	0.4	2.5	0.1	3.2	1.45

the largest share of rain-fed (56.6%), and Char Mahal Bakhtiari, Khorasan Razavi, Kerman, and Yazd have the most significant share of irrigated almond orchards (40%). However, based on the crop yield, the irrigated orchards of Tehran (3 ton ha^{-1}) and the rain-fed orchards of Khuzestan (1.8 ton ha^{-1}) provinces rank first irrigated. The average yields in Iran's irrigated and rainfed orchards are 1.5 and 0.42 kg ha^{-1}, respectively (Table 1).

In this regard, the yearly averages of nitrate chemical fertilizer consumption are about 41 and 54 kg ha^{-1} for the rain-fed and irrigated conditions.

Almond water footprint in Iran

The value of WF components obtained for irrigated and rain-fed almonds is displayed in Table 2. In rain-fed orchards, the green WF contains values between 0.5 and 13.5 m^3kg^{-1}, while the grey WF takes values from 0.2 to 8.4 m^3kg^{-1}. The total average of WF for rain-fed orchards

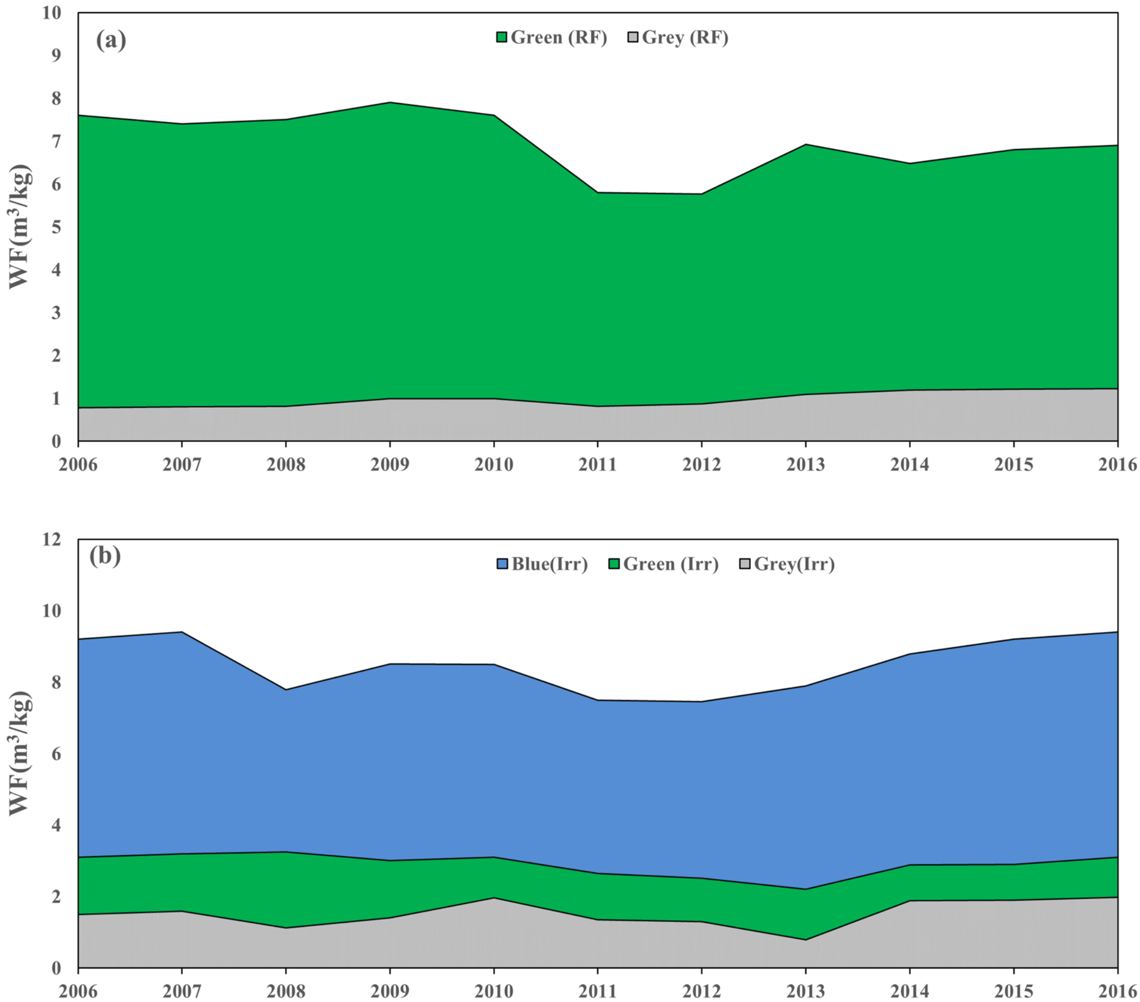

Fig. 3 Shares of WF components in the rain-fed (**a**) and irrigated (**b**) almonds in Iran

is 9.2 m^3kg^{-1}, sharing 72% of WF_{Green} and 28% of WF_{Grey}. Kohgiluyeh & Boyer-Ahmad (91%) and Ilam (90%) have the highest, and Boshehr (32%) has the smallest share of WF_{Green}.

For irrigated almonds, the values of WF_{Green} are between 0.4 and 7.2 m^3kg^{-1}, the amounts of WF_{Blue} are from 2.5 to 26.4 m^3kg^{-1}, and finally, the WF_{Grey} values range from 0.1 to 6.4 m^3kg^{-1}. In addition, the total average of WF for the rain-fed almonds is 11.4 m^3kg^{-1} with a combination of 19% green, 71% blue, and 10% grey (Fig. 3). For the irrigated orchards, the average of WF_{green} is about 2.2 m^3kg^{-1} in which the most significant shares belong to Kohgiluyeh & Boyer-Ahmad (36%), Ilam (35%), and Kermanshah (34%), and the lowest shares obtained by Yazd (4%), Qom (6%), and Sistan & Balochestan (8%), respectively.

The blue WF, with 8 m^3kg^{-1}, contributes the largest share of WF in almond production. The results show that Sistan & Balochestan (90%), Khouzestan (89%), and Hormozgan (88%) have the largest shares of WF_{Blue}. In contrast, Kohgiluyeh & Boyer-Ahmad (49%), Azerbaijan-Gharbi (49%), Kermanshah (54%), and Lorestan (60%) have the lowest shares in WF_{Blue} In this situation; the grey WF is calculated 1.1 m^3kg^{-1} for almond production. According to the results, Azerbaijan-Gharbi (16.8%), Qazvin (15.6%), and Azerbaijan-Sharghi (15.2%) contribute the largest share of grey WF, while Khouzestan (2%) and Khorasan Jonoobi (2.4%) have the lowest shares.

The share of WF components for the irrigated and rain-fed almonds during 2006–2016 are displayed in Fig. 3. As shown, the share of green WF has decreased, while the share of grey WF has increased for the rain-fed almonds. In general, the share of WF components in irrigated almonds has increased during the study periods.

Economic water footprint (WFE)

Table 2 indicates the average economic water footprint for irrigated and rain-fed almonds during the study period.

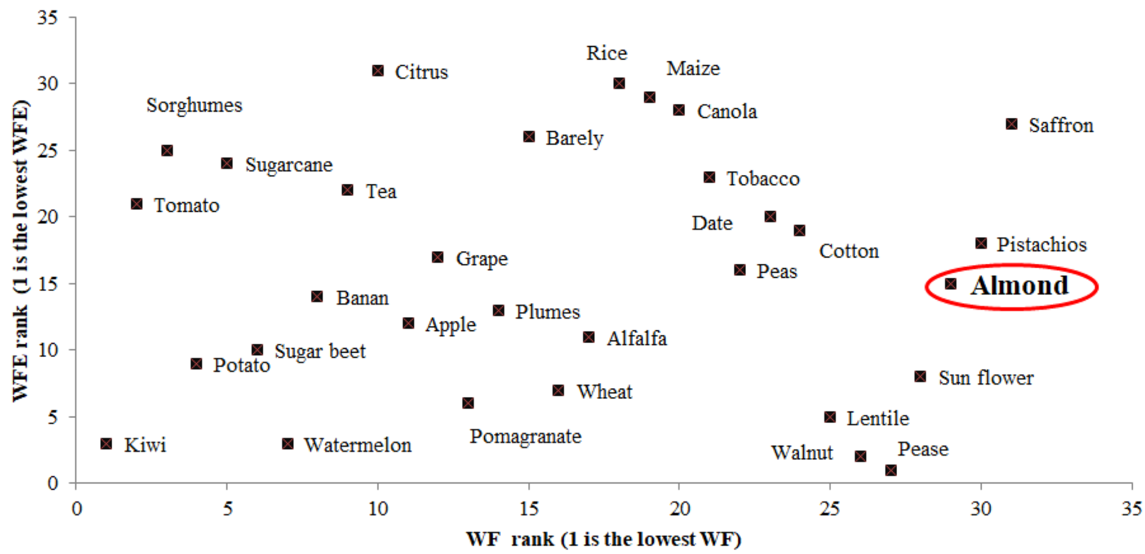

Fig. 4 Crops ranking based on WF and WF_E in Iran the duration of 2006–2016

The results show that about 2.8 m^3 of water is needed to earn one dollar benefit from rain-fed almonds; this value is 5.16 m^3 for irrigated almonds. This means that more surface water and groundwater are needed to make a net benefit from irrigated almonds. In contrast, the rain-fed almonds only use the precipitation for one dollar net benefit, so the water resources remain untouched. In addition, more affordable products go out to domestic and international markets, spending less money and less water. Finally, considering the almost equal share of irrigated and rain-fed almonds, the weighted WF_E of almond products in Iran is about 4 m^3 $US\$^{-1}$.

Based on WF_E values in Table 2, Azerbaijan Shargi (17.36 m^3 $US\$^{-1}$) has the highest and Tehran (1.45 $m^3US\$^{-1}$) the lowest WF_E of irrigated almonds. Furthermore, the highest and lowest WF_E belong to Khorasan Razavi (6.03 $m^3US\$^{-1}$) and Khouzestan (0.22 $m^3US\$^{-1}$) in rainfed orchards. Thus, Tehran and Khouzestan have the lowest WF_E in irrigated and rainfed almond production and provide higher economic value and lower water consumption to domestic and foreign markets (Table 2).

The comparison between WF_E of almonds and 30 main agricultural products in Iran (Bazrafshan et al. 2020, 2019a) is illustrated in Fig. 4. In this figure, the *x*-axis represents crops ranking based on WF, with 1 for the lowest and 31 for the highest WF per one kilogram; and the *y*-axis demonstrates crop ranks in terms of WF_E, with 1 being the lowest and 31 the highest. The result shows that the almond is ranked 29th in WF and 15th in WF_E.

Temporal variations of WF_E components for the irrigated and rainfed almonds are displayed in Fig. 5. As shown, the WF_E of rainfed almonds is less than the irrigated product. From 2010 to 2012, the WF_E decreased due to increased crop yield in both production methods.

Water footprint at the national and provincial level

The total volume of AWF (Table 3) indicates that an average of 1923MCM was used in rainfed almond production yearly. From this amount, the share of green and grey WF are 1272.5 and 650.8 MCM, respectively. Khorasan Razavi and Fars have the highest volume (1172 MCM, which equals 61% of the total) of virtual WF in rain-fed almond production. The weighted average of AWF in irrigated almonds is 8244 MCM per year, in which the share of green, blue, and grey WF is 868.8, 5881, and 1494.2 MCM, respectively.

The highest volume of AWF belongs to Azerbaijan Sharghi (1849 MCM), Qazvin (943.8 MCM), and Khorasan Razavi (658 MCM) in irrigated almonds equal the 41.5% of the total AWF proportion. In addition, the shares of $WF_{Blue} + WF_{Grey}$ in these provinces are 86%, 77%, and 81% (Table 3), respectively. In addition, the total volume of AWF in Iran is about 10167.3 MCM per year for irrigated and rain-fed almonds. The consumption of almonds is 0.5 kg (MAJ 2018) in Iran per capita, with a population of 80 million [Statistical Centre of Iran (SCI 2017)], where 824 MCM yr^{-1} are used inside Iran, and 9343MCM yr^{-1} are exported overseas.

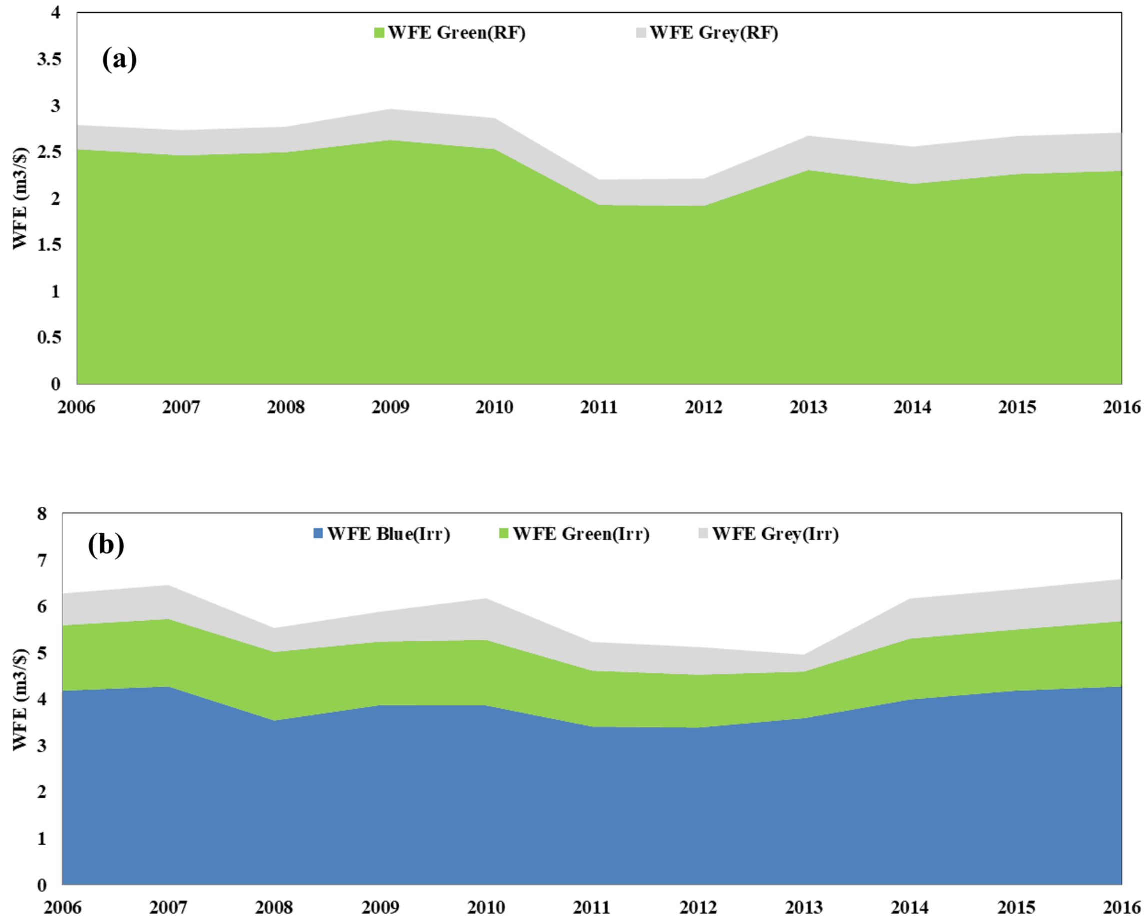

Fig. 5 Temporal variations of WF_E for rain-fed (**a**) and irrigated (**b**) almond

The annual variations of AWF in irrigated and rain-fed almonds are displayed in Fig. 6. As shown, the volume of AWF decreased from 2010 to 2012, but in general, the volume of AWF is increasing in Iran.

Spatial prioritization of rain-fed and irrigated almonds

To classify the provinces based on the production of rain-fed and irrigated almonds, the K-means clustering approach has been implemented based on WF_E and WF variables. The spatial priority patterns of rain-fed (Fig. 7a) and irrigated (Fig. 7b) almonds are represented in Fig. 7.

The results of rain-fed clustering (Fig. 7a) showed that the provinces could be divided into five clusters in terms of green, blue, and grey WF with very high, high, middle, low, and very low priorities. In this regard, Khouzestan, with the lowest green and grey WF and WF_E, is placed in the very high-priority category of production rainfed almonds. In addition, Khorasan Jonoobi and Alborz are located in high-priority clusters. The middle priority cluster contains Yazd province due to its different climate from other provinces. The low priority cluster consists of Hamedan, Fars, Ilam, Isfahan, Ardabil, and Chaharmahal & Bakhtiari because of their similarity in WF and WF_E. Finally, Kohgiluyeh&Boyer-Ahmad, Azerbaijan Sharghi, Kurdistan, Markazi, Hamedan, Kerman, Khorasan Razavi, Kermanshah, Khorasan Shomali, Lorestan, Zanjan, and Azerbaijan Gharbi belong to the lowest priority cluster. These provinces have the lowest crop yield and the highest green and grey WF and WF_E.

The priority clustering of irrigated almonds is very different from those given in rain-fed almonds. The highest priority cluster contains Alborz, Khouzestan, and Tehran. The second cluster of irrigated almond cultivation contains Zanjan, Chaharmahal&Bakhtiari, and Fars. The third cluster with the middle priority of almond cultivation contains Boshehr, Hormozgan, Isfahan, Semnan, Sistan&Balochestan, and Kerman. The fourth cluster consists of Lorestan, Kermanshah, Ardabil, Kurdistan, Markazi, Qom, Khorasan Razavi, Azerbaijan Sharghi, and Khorasan Shomali, with a low priority on almond cultivation. The majority of these provinces are located in semi-arid climates. The high chemical fertilizer consumption and low crop yield have caused them to be classified as a low-priority cluster.

Table 3 Total volume of AWF components for the rain-fed and irrigated almonds

Province	$AWF_{Rain\text{-}fed}$ (MCM)			$AWF_{Irrigated}$ (MCM)				National share (%)	
	Green	Grey	Total	Green	Blue	Grey	Total	Rain-fed	Irrigated
Azerbaijan Shargi	32 (67%)	16.1 (33%)	48.1	262.5 (14%)	1279.1(69%)	308.1 (17%)	1849.7	2.5	22.4
Azerbaijan Gharbi	13.4 (90%)	1.5 (10%)	14.9	67.6 (30%)	122.1 (54%)	35.5 (16%)	225.2	0.8	2.7
Ardabil	4.6 (84%)	1.0 (16%)	5.5	1.8 (24%)	5.1 (67%)	0.7 (9%)	7.6	0.3	0.1
Isfahan	10.9 (69%)	4.8 (31%)	15.7	55.9 (13%)	350.2 (83%)	17.9 (4%)	424	0.8	5.1
Alborz	0.1 (99%)	0.001 (1%)	0.1	1.9 (24%)	5.7 (73%)	0.2 (3%)	7.8	0.0	0.1
Ilam	7.8 (91%)	0.8 (9%)	8.6	6.2 (36%)	9.2 (53%)	1.9 (11%)	17.3	0.4	0.2
Boshehr	0.1 (50%)	0.1 (50%)	0.2	0.1 (14%)	0.6 (86%)	0.001 (0%)	0.7	0.01	0.01
Tehran	–	–	–	2.3 (20%)	9.2 (78%)	0.2 (2%)	11.7	–	0.1
South Kerman	–	–	–	1.3 (11%)	9.6 (86%)	0.3 (3%)	11.2	–	0.1
Chaharmahal & Bakhtiari	3.1 (79%)	0.8 (21%)	3.9	167.5 (26%)	443.1 (70%)	21.5 (4%)	632.1	0.2	7.7
Khorasan Jonoobi	59.2 (71%)	24.3 (29%)	83.5	36.1 (12%)	242.3 (84%)	10.6 (4%)	289	4.3	3.5
Khorasan Razavi	419.2 (57%)	322.4 (43%)	741.5	121.5 (18%)	471.6 (72%)	64.2 (10%)	657.3	38.6	8.1
Khorasan Shomali	99.6 (56%)	77.4 (44%)	177.0	22.2 (22%)	68.5 (69%)	8.7 (9%)	99.4	9.2	1.2
Khouzestan	0.3 (75%)	0.1 (25%)	0.5	0.3 (9%)	3.1 (89%)	0.1 (2%)	3.5	0.01	0.01
Zanjan	10.0 (87%)	1.5 (13%)	11.6	37.9 (26%)	91.7 (62%)	18.4 (12%)	148	0.6	1.8
Semnan	–	–	–	6.9 (11%)	52.3 (85%)	2.2 (4%)	61.4	–	0.7
Sistan & Balochestan	–	–	–	0.7 (7%)	9.6 (90%)	0.3 (3%)	10.6	–	0.1
Fars	341.1 (79%)	89.4 (21%)	430.5	102.1 (21%)	367.5 (76%)	15.3 (3%)	484.9	22.4	5.9
Qazvin	106.0 (84%)	20.7 (16%)	126.6	217.5 (23%)	571.5 (61%)	154.8 (16%)	943.8	6.6	11.4
Qom	–	–	–	6.3 (9%)	60.1 (83%)	5.8 (8%)	72.2	0.01	0.9
Kurdistan	15.3 (88%)	2.1 (12%)	17.4	11.7 (32%)	22.1 (60%)	2.9 (8%)	36.7	0.9	0.4
Kerman	25.0 (43%)	33.0 (57%)	58.0	63.1 (11%)	501.8 (84%)	35.3 (5%)	600.2	3.0	7.3
Kermanshah	40.1 (55%)	32.2 (45%)	72.3	38.7 (35%)	69.4 (62%)	4.0 (3%)	112.1	3.8	1.4
Kohgiluyeh & Boyer-Ahmad	10.3 (91%)	1.0 (9%)	11.3	27.5 (36%)	37.3 (49%)	11.3 (15%)	76.1	0.6	0.9
Lorestan	10.6 (82%)	2.4 (18%)	13.0	52.1 (34%)	93.8 (61%)	8.0 (5%)	153.9	0.7	1.9
Markazi	5.6 (75%)	1.9 (25%)	7.5	80.1 (24%)	236.6 (71%)	17.4 (5%)	334.1	0.4	4.1
Hormozgan	–	–	–	5.4 (9%)	54.9 (87%)	2.5 (4%)	62.8	–	0.8
Hamedan	57.9 (78%)	16.8 (22%)	74.8	69.7 (28%)	159.7 (64%)	18.4 (7%)	247.8	3.9	3.0
Yazd	0.3 (38%)	0.5 (63%)	0.8	27.3 (4%)	533.3 (80%)	102.3 (15%)	662.9	–	8.0
Sum	1272.5	650.8	1923.3	1494.2	5881	868.8	8244	100	100
Average	53.0	27.1	80.1	51.5	202.8	30.0	284.3	–	–
Max	419.2	322.4	741.5	262.5	1279.1	308.1	1849.7	38.6	22.4
Min	0.1	0.001	0.1	0.1	0.6	0.1	0.7	0.01	0.01

Finally, the fifth cluster with very low priority contains Qazvin, Kohgiluyeh&Boyer-Ahmad, Ilam, Azerbaijan Gharbi, and Yazd provinces. The high WF_E in these provinces has caused them to be located in the lowest priority cluster of irrigated almond cultivation.

Discussion

To assess the influence of almond production on water resources in Iran, the temporal and regional variation of irrigated and rainfed WF and WF_E has been computed and compared with other crops from 2006 to 2016.

Water footprint components

The total average of WF in almond production in Iran is about 10.4 m^3kg^{-1}. This value is 8.074 m^3kg^{-1} on the global scale (Mekonnen and Hoekstra 2011); 6.7 m^3kg^{-1} in Australia (Hossain et al. 2021); 20.24 m^3kg^{-1} in California (Fulton et al. 2019); and 20.8 m^3kg^{-1} in Tunisia (Chouchane et al. 2015). Differences in management of planting, growing, and harvesting, excessive fertilizer consumption in low-yield agriculture lands, climatic conditions, water use, latitude, and soil type are the main factors leading to various WFCs in different regions.

The results of the current study concerning the total national WF (green + blue and grey = 10.4 m^3/kg) of

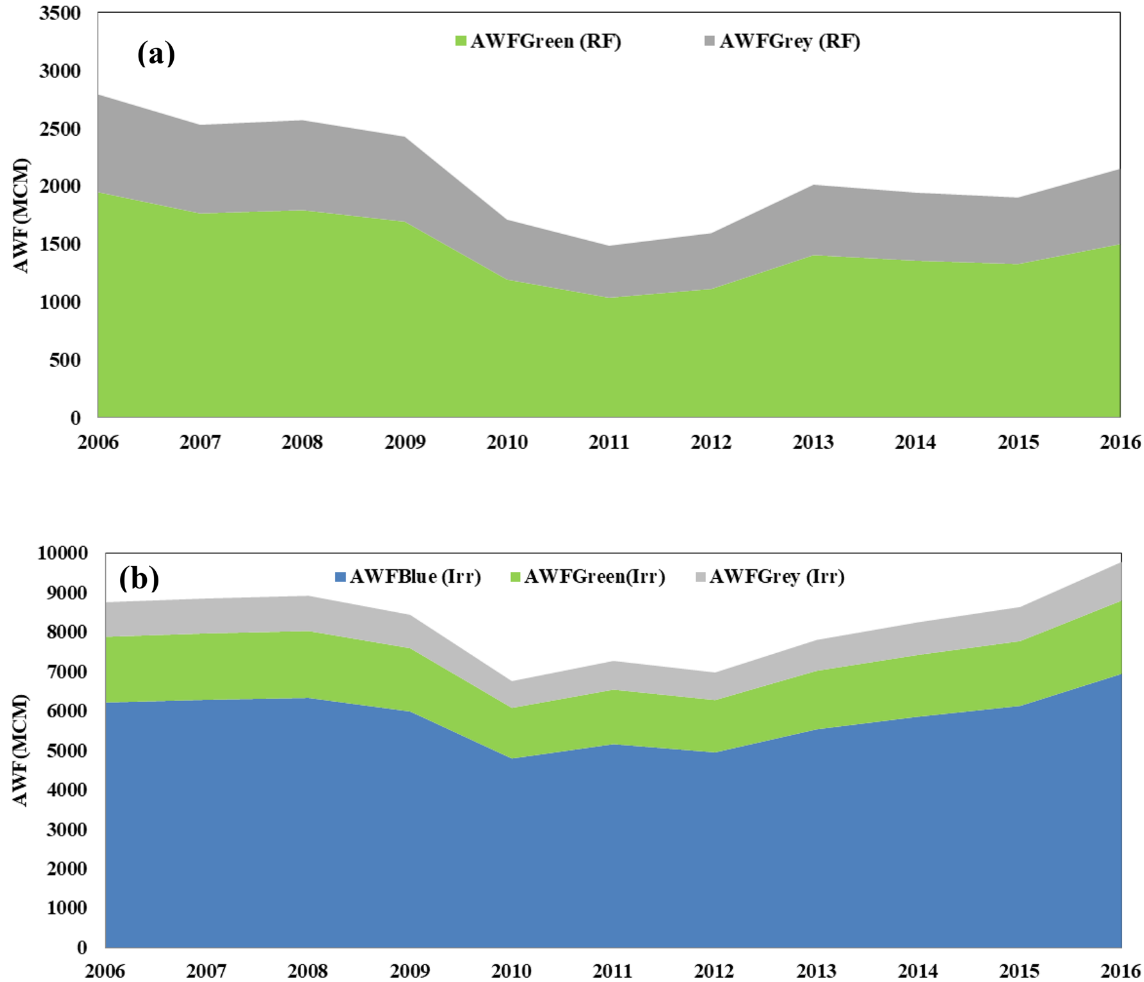

Fig. 6 Temporal variations of total volume AWF for rain-fed (**a**) and irrigated (**b**) almonds

almond production can be compared to global studies by Chapagain and Hoekstra (2004). This result shows Iran's total WF (green + blue) of almond production was 10.374 m^3/kg. Chapagain and Hoekstra (2004) obtained the climatic data from the online database of the Tyndall Centre for Climate Change and Research (Mitchell and Jones 2005). As there are considerable spatial variations among the studied provinces and provinces, the average data at a national scale could result in biased estimates of WFCs.

Also, they used a grid-based dynamic water balance model to calculate CWU and crop yield, while in the current study, the actual average yields at a provincial scale were combined with a calibrated model (CROPWAT) for estimating the irrigation requirements.

The significant difference between ETc, P_{ef}, IR in each province indicates that more minor scales should be considered to evaluate indices. In general, the studied values at the provincial level are more accurate than those on a national or global scale.

On the other hand, in modeling yield variables, various assumptions about input variables affect the amount of green water footprint. In the case of blue water, it should be noted that using real irrigation data will lead to a more accurate estimation of water footprint. Therefore, estimated parameters in regional studies have higher validity and less uncertainty than the national studies.

The estimated yield of irrigated and rain-fed almonds is about 1.5-ton ha^{-1} and 0.5 ton ha^{-1}, respectively, during the study period in Iran. The almond yield is very high in some countries, such as the USA (2.2 ton ha-1) and Spain (2.67 ton ha-1). In terms of the average yield of almonds, Iran is ranked 12th among the top 20 producing countries (FAO 2018). According to the MAJ (2018), several factors such as *Candidatus Phytoplasma phoenicium* (one of the most destructive diseases of almond orchards), old-age and non-grafting of almond trees, frost-bite of almond trees, high evapotranspiration rate, the low harvesting and planting technology, blossom drop, inappropriate farming land, and persistent droughts have caused a reduction in almond yields

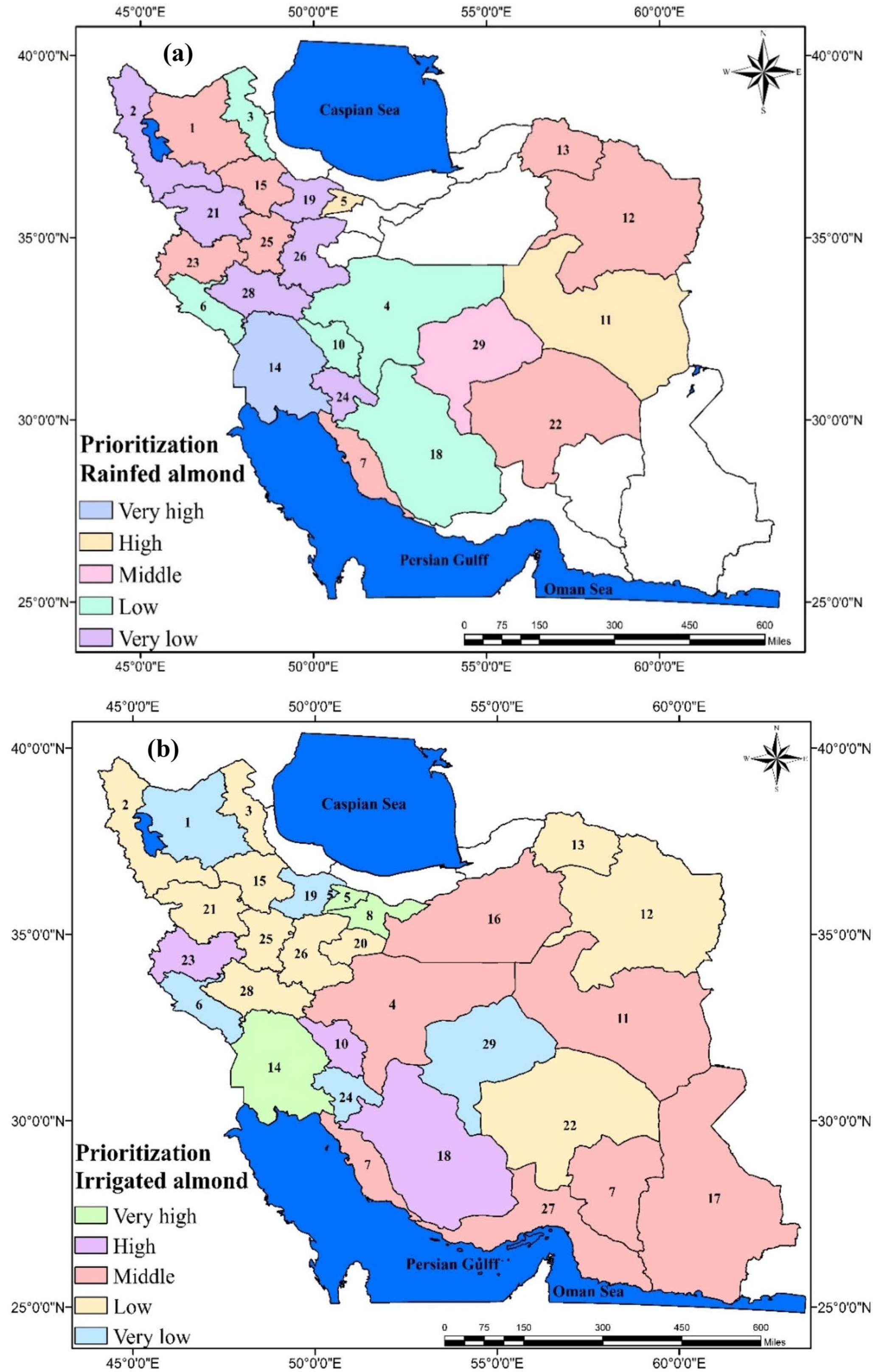

Fig. 7 Regional prioritization in rainfed (**a**) and irrigated (**b**) almond based on WF and WF_E indices using K-means clustering

in Iran since 1994. Therefore, using genotypes resistant to dehydration, frost-bite, and drought, frost-bite control with existing technologies, nutritional balance of almond trees, mulching treatment, and use of low evapotranspiration cultivars can increase crop yield (Kiani and Malakouti 2000).

The temporal variation of irrigated and rain-fed almond WFCs has increased during the study period except for 2010–2012. Based on Teimouri and Bazrafshan (2017), many parts of Iran experienced more rainfall in this period than the long-term average. However, it seems that the increase in WF in almond orchards in Iran is due to reduced yield per unit area, increased water demand and evapotranspiration due to drought and climate change, poor soil and water quality, high chemical fertilizer consumption, water losses, and new almond orchards that have little yield (Seyyed Abdolahi et al. 2020).

Regional variations of WF show a decreasing trend from the northern to the southern end of Iran, especially in Khouzestan, Yazd, Fars, and Kerman. In these regions, the yield per unit area is considerable. This better yield is due to the warmer climate in the southern regions. Although the reduction of evapotranspiration affects WF, the increasing temperature has more effects on yield, leading to WF reduction (Fulton et al. 2019).

Total volume of water footprint

While rain-fed almonds occupy around 49% of total almond orchards, the total volume of WF is only one-quarter of that of irrigated orchards in Iran. The Irrigated almond orchards in Iran depend entirely on groundwater. Excessive water consumption and climate change have presented Iran with a water shortage crisis. Although Iran has significant rankings in the production of many agricultural products, it has performed very poorly in knowledge-based development and new technologies in the agricultural sector. Inadequate cropping patterns, low productivity irrigation systems, small-farming systems, and low-level technologies of planting and harvesting are some of the most critical challenges in the agricultural sector in Iran (MAJ 2018). Therefore, practical agricultural management toward utilizing precipitation for improving rain-fed orchards has caused less pressure on existing water resources, especially in some provinces such as Fars, Khorasan Razavi, and Kerman that are faced with a severe water crisis.

The spatial distribution of WF_{Green} for irrigated and rain-fed almonds is different in Iran due to differences in climate, amount of precipitation, and soil type. Since the West and Southwest provinces (Ilam, Kermanshah, Kurdestan, Khousestan, and Chaharmahal &Bakhtiari) have high P_{eff} and WF_{Green}. They are suitable for the development of rain-fed almond cultivation. In general, water harvesting using rainwater catchment systems, such as terrace and banket, using water stress-resistant cultivars, expansion of agroforestry systems in almond orchards, and use of the mulches and superabsorbents to reduce evaporation from the soil surface can promote the rain-fed cultivation in susceptible regions (Rahemi and Yadollahi 2006; Karimi et al. 2019).

The volume of AWF_{grey} in irrigated and rain-fed almonds equals 1427 MCM per year used for diluting chemical fertilizers. High fertilizer consumption in Iran is due to the poor soil, especially in arid and semi-arid (e.g., Yazd, Isfahan, Khorasan Razavi, Zanjan, and Qazvin) and high leaching of Mediterranean regions (e.g., Ilam, Lorestan, Hamedan, and Markazi). Therefore, using methods such as a tillage system, nutrient elements added for balance in the soil, crop rotation, farm management, bio-fertilizer consumption, the use of wholly matured animal manure, irrigation management (nutrient uptake is not performed properly if the soil moisture is not optimal) and, most importantly, policies and training to raise farmers' awareness and attitudes of the destructive long term effects of the use of chemical fertilizers. (Yazdani et al. 2019), to reduce not only the gray water footprint but also reduce water and soil pollution.

The share of blue WF in Iran is about 70%, with a total volume of 5881 MCM. Around 70% of almond orchards in Iran are located in arid and semi-arid provinces (e.g., Yazd, South Kerman, and Semnan) with less precipitation and high evapotranspiration and water requirement. The blue WF increased in these provinces because of using traditional and inappropriate irrigation systems.

About 24% of orchards in Iran are currently irrigated with modern methods, in which water use efficiency is reported to be 45% (MAJ 2018). Developing new irrigation methods and increasing water use efficiency can reduce the blue water footprint in these areas.

The water efficiency index is one of the most important criteria for optimal water consumption in the agricultural sector. This index was reported 0.8 kg/m^3 at the beginning of the fourth program in Iran, and during the 20-year program, it should reach 1.6 kg/m^3 (Abbasi et al. 2016).

Deficit irrigation management is another method for reducing water footprint in areas with high footprint almond orchards. Deficit irrigation is a suitable way to produce crops in water deficit conditions that consciously allow plants to produce more by receiving less water. Deficit irrigation increases water use efficiency (Alcon et al. 2013).

According to the results, the highest almond cultivation area belongs to Chaharmahal &Bakhtiari, Khorasan Razavi, Kerman, and Yazd. Shortage of surface runoff and water crisis has caused the total water requirements in these provinces to be supplied by groundwater. Actual water resources in these provinces are surface water, groundwater, and transitional water. The amount of groundwater abstraction in the Kerman, Yazd, and Khorasan Razavi provinces is 60% higher than the world standard, which has caused salinization of water and agricultural lands, land subsidence, and falling groundwater level (Abbasi and Abbasi 2020).

Using unconventional water resources such as agricultural–urban and industrial wastewater, saline, brackish water, and cloud seeding can compensate for water shortages in the agricultural sector. According to Yargholi and Azarneshan (2014), unconventional water resources in Iran are 45 billion cubic meters, of which only 1 billion cubic meters of water is recycled and reused in agriculture.

Water footprint accounting

The average annual WF_E is rain fed, 2.88 and irrigated, 5.16 m^3 $US\$^{-1}$, while the total average is about 3.98 m^3 $US\$^{-1}$. The difference between WF_E in rain-fed and irrigated almonds in Iran is 2.28 m^3 $US\$^{-1}$, which is non-negligible. However, in different provinces, there can be seen a greater difference between WF_E and WF in rain-fed and irrigated almonds (e.g., Azerbaijan Sharghi, Yazd, Ilam, Qazvin, and Qom). In particular, East Azerbaijan, Qazvin, and Ilam provinces spend less water on rainfed almonds to earn one dollar. These provinces are located in the Mediterranean climate and have good green water reserves.

Undoubtedly developing rain-fed almond orchards in those areas, with attention to the effective rainfall, soil type, and use of water stress-resistant cultivars will reduce dependence on blue water, increasing the economic value and decreasing the WF_E.

According to a survey on trading virtual water, only 8% of total almond WF has been used in Iran, and 92% was exported to other countries, such as United Arab Emirates, Turkey, Qatar, Turkmenistan, Afghanistan, India, Bahrain, and Kuwait (MAJ 2018). The average of exported WF_E in irrigated and rain-fed conditions is 3.98 m^3 $US\$^{-1}$. According to clustering results that were implemented on WF_E of agricultural products in Iran (Arabi Yazdi et al. 2009; Bazrafshan et al. 2020), the products were classified into six groups (appendix I), including very low, low, middle, high, very high and extreme. The almonds, along with apples, grapes, and plums, are clustered in the middle category.

Almonds, such as dates, pistachios, raisins, and saffron, are among Iran's most important non-oil exports, with about 4 million dollars in foreign exchange earnings for the country (MAJ 2018). However, with more attention, it has much potential for the growth of the national economy. In this regard, improving packaging methods and implementing supportive and incentive policies should be considered essential factors for increasing the competitiveness of these products at the international level.

Considering 2.6 US\$ Kg^{-1} net benefit for dried almonds with shell (average of rainfed and irrigated), and the average of 10.4 m^3Kg^{-1} for WF, the value of one cubic meter of exported water will be 0.25 US\$ m^{-3}. However, this value was 0.09 US\$ m^{-3} in Tunisia and 0.42 US\$ m^{-3} in California.

Although increasing performance and reducing footprint affect WF_E, the net benefit index significantly affects WF_E. Furthermore, the net benefit greater than zero indicates that the product has a comparative advantage. Increasing performance, reducing costs, and improving technology increase net profit or comparative advantage. However, the comparative advantage is not a static advantage, because it changes over time under many factors, such as water, land, labor, packaging, transportation, marketing, market fluctuations, and advertising. Thus, to increase WF_E in Iranian orchards, a long-term increase in net profit and comparative advantage must be sought (Yazdani et al. 2005).

While almond WF ranks 29 among 30 main agricultural products in Iran, it ranks 15 in WF_E, which is better than many other exported products, such as saffron and pistachios.

Comparing almonds with 30 main agricultural products in Iran indicated that they are almost the same as pistachios ($WF_E = 18$; $WF = 30$) in terms of water footprint (rank 29) and economic value (rank 15) but are lower than the walnut ($WF_E = 2$; $WF = 26$). Pistachio and almond orchards have increased costs due to the difficult conditions of production and cultivation, late maturity and fertility, and low tree productivity (Khosh-Khui et al. 2015).

Prioritizing provinces based on WF and WF_E in irrigated and rain-fed almonds reveals several facts. For instance, improper irrigation management, low crop yield, and high fertilizer consumption and leaching have led several of those provinces (e.g., Ilam, Azerbaijan Sharghi, Lorestan, and Kermanshah) with desirable climatic conditions, storage of green water, and soil condition to be ranked in the lowest priorities. These provinces generally are located in Western and Northwestern Iran, where appropriate planting and fertilizer management could turn those into almond-producing centers of Iran.

In general, the results of WF and WF_E analysis in this study in 29 provinces of Iran indicate that all parts of Iran do not have enough capacity for optimal production of rain-fed and irrigated almonds. However, in any region, the nut crops industry can flourish due to the favorable climatic and soil conditions and strategies for reducing the water footprint. It seems that the prospect for the cultivation of this crop in Iran is very promising, if from now on, applied methods in field management, irrigation management, post-harvesting, and marketing management provide the necessary grounds to increase production and improve product quality are used.

The results of this research show that significant groundwater savings can be achieved when farmers would reduce AWF blue and AWF Grey of almond production to certain reasonable levels. This is possible when provinces with low and very low priority (14 out of 29 provinces) stop or reduce irrigated almond cultivation. These provinces account more than 70% of the total volume of blue and gray water in almond production in Iran. Reducing the cultivation area in these provinces will lead to considerable water savings in ground water resources.

Conclusion

Water and economical water footprint are appropriate for regional prioritizing in arid and semi-arid climates. Combining WF and WF_E with different scales provides appropriate information for managing water resources.

During the study period, the WF and WF_E of almonds increased, while their yield and economic value decreased. Because of two decades of sweeping droughts, most of Iran's irrigated almonds were produced using blue and grey water. The results of this research are not the only source for evaluating sustainable almond production in low-water areas when the almonds are produced through excessive groundwater extraction. On the other hand, assessing these indices can be an essential step in sustainable almond production in Iran, because, in addition to WF per kg, WF_E, and economic value, the total available water, and water impact in each region should be considered.

Water resources are very limited in Iran, especially in the middle regions, where water scarcity has increased due to the government's water policy over the past two decades. During the past decades, the Iranian government's policy was self-sufficiency in strategic products. There was no control over production, development, cultivation, or the exporting and importing of agricultural products with any thought about virtual water, economical water footprint, and water footprint (MAJ 2018). However, recently, it has been indirectly considered in Iran's sixth plan development (IPRCIRI 2021). Despite the previous development plans in Iran, according to the sixth development plan, it is impossible to extract more water resources in Iran, rather 11 billion cubic meters less should be extracted from the groundwater resources. The economic effects of this reduction in extraction must be compensated through increasing water productivity in the Agricultural sector, increasing yield per unit area, water demand management, using agricultural and garden varieties resistant to water stress and salinity, and optimization of cultivated area based on the above factors. Although WF/VW is not mentioned directly in this program, the above solutions indicate that water managers and policy makers are indirectly realizing this vision in managing water resources, food security and economical stability in the agricultural sector in Iran for the next development plans.

Finally, the results of this study showed that water footprint and economical water footprint indices provide helpful information for prioritizing cultivation in potential areas. Combining these indices with local and regional information results in the optimal management of water resources, which can be used in allocating water resources to cultivate policy-making on provincial and national scales.

Appendix

See Table 4

Table 4 Classified of economic water footprint ($WF_{Green}+WF_{Blue}$) for main crops in Iran (Arabi Yazdi et al., 2009; Bazrafshan et al. 2020)

Crops	$WF_{E(Green+Blue)}$ ($m^3\$^{-1}$)	Range	Description of WF_E
Group 1			
Tobacco	0.06		
Kiwi	0.09		
Banana	0.124	0.01–0.49	Very low
Sugarcane	0.3		
Pomegranate	0.32		
Tea	0.36		
Group 2			
Grape	0.61		
Pistachios	0.76	0.51–0.99	Low
Rice	0.8		
Group 3			
Watermelons	1.1		
Apple	1.23		
Almond	1.26		
Citrus	1.4	1–1.89	Middle
Plumes	1.43		
Canola	1.56		
Potato	1.63		
Saffron	1.66		
Group 4			
Tomato	1.92	1.9–2.49	High
Wheat	2.1		
Group 5			
Sugar beet	2.5		
Beans	2.55		
Barley	2.6		
Date	2.66		
Alfalfa	2.84	2.5–3.99	Very high
Cotton	2.9		
Lentils	2.97		
Maize	3		
Peas	3.33		
Group 6			
Sun flower	4.3	> 4	Extreme
Sorghum	4.4		

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