

Water Footprint Assessment and Sustainability Evaluation of Jalizi Crop Production Systems in the Hyperarid Sistan Region, Iran

Somayyeh Mirshekari*¹ 

¹ Agriculture Institute, Research Institute of Zabol, Zabol, Iran.

*Corresponding Author: Email: (SMirshekari@rizabol.ac.com)

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Abstract: This study examines the water footprints of five jalizi crop production systems (Gandak, Sefidak, Pashmak, watermelon and melon) through a questionnaire survey of 277 farms. Blue, green and grey water footprints were calculated following the Water Footprint Assessment Manual, and physical and economic water productivity were evaluated alongside correlation analysis with energy-based sustainability indices. Total water footprint ranged from 513.6 to 849.2 m³ ton⁻¹, a variation of 65 %, with Pashmak recording the lowest value. The blue component dominated every system (43.8–83.5 %) in this hyperarid environment, where only 54 mm of rain falls annually and irrigation is therefore the sole practical water source, while the grey component arising from nitrogen fertilization contributed 15.5–55.5 %. Green water footprints were negligible (< 1.1 %) because rainfall is minimal. Pashmak proved the most efficient system, with the highest physical (1.95 kg m⁻³) and economic (58,416 Toman m⁻³) water productivity, which is attributable to its abbreviated growing season of 2.5 months. A strong negative correlation was found between total water footprint and energy renewability ($r = -0.955$, $p = 0.011$), which confirms the complementary nature of the two assessment approaches. Conversion to drip irrigation, reduction of nitrogen application from 950–1,050 to 200–300 kg ha⁻¹, and adaptive crop selection emerge as the principal measures for improving water sustainability in this water-stressed production system.

Keywords: Water footprint; Blue water; Grey water; Jalizi crops; Water productivity

1. Introduction

Water scarcity has become one of the greatest threats to global food security in this century. Agriculture accounts for approximately 70 % of all freshwater withdrawals worldwide (FAO, 2022), and the pressure is intensifying. Climate change, population growth, and competition from cities and industry place additional strain on resources that are already stretched, particularly in arid and semi-arid zones where farming depends most heavily on irrigation (Rosa et al., 2020). The United Nations has projected that water demand could exceed supply by 40 % by 2030 if current trends continue (UN-Water, 2021).

Water footprint (WF) assessment offers a response to this problem. Traditional irrigation efficiency metrics capture only what happens at the field scale, whereas the water footprint accounts for blue water (surface water and groundwater), green water (rainfall), and grey water (the volume required to dilute pollution). The result is a complete picture that can identify problem areas and guide optimization (Hoekstra et al., 2021; Zhuo & Hoekstra, 2022). Studies applying WF methods to crops have shown wide variation depending on region, farming practice, and crop type, and water savings of 30–60 % appear achievable through better technology and management (Chukalla et al., 2020; Mekonnen & Hoekstra, 2020).

The Sistan plain in southeastern Iran (30°12' to 31°28' N; 61°16' to 61°50' E) is an extreme case of the

water–food security challenge. Its climate is hot and hyperarid (BWh classification), annual rainfall is only 54 mm, and potential evapotranspiration exceeds 4,000 mm per year, which places the plain among the most arid agricultural regions on Earth (Dehghanipour et al., 2020). The "120-day winds," the relentless northwesterly gales that blow from June through September, raise evaporative demand further and make farming harder still (Rashki et al., 2021).

Agriculture in the region depends almost entirely on the Hirmand River (the Helmand in Afghanistan), which historically supplied 5–7 billion m³ annually but now delivers less than 1 billion m³ as a result of upstream dams, persistent drought, and climatic shifts (Alizadeh-Choobari & Najafi, 2022). The Hamoun wetlands have dried up, land degradation is widespread, and more than 500,000 people who relied on farming for their livelihoods have been severely affected (Sarhadi et al., 2023).

Within this difficult context, jalizi crops hold real cultural and economic importance. Various melon (*Cucumis melo*) and watermelon (*Citrullus lanatus*) cultivars occupied around 7,000 hectares in 2020 and yielded 150,000 tons worth over 1,500 billion Iranian Rials (about USD 35 million), which represents 8–10 % of regional agricultural GDP (Statistical Center of Iran, 2021). The production systems include improved varieties (Gandak, cv. Firoozi 77), locally adapted landraces (Sefidak), early-harvest specialty systems

(Pashmak), and standard watermelon and melon cultivars. Despite their economic significance and heavy water use, water sustainability in these systems has not previously been assessed systematically, which leaves a substantial knowledge gap.

Sustainability science has been moving toward integrated assessment that combines several methodological perspectives. Emergy analysis, developed by Odum (1996), quantifies all resource inputs using solar emergy as a common unit and thereby allows environmental support requirements, renewability, and efficiency to be evaluated together (Brown & Ulgiati, 2021). Our earlier work found that jalizi crops in Sistan show emergy renewability ranging from 3.06 % to 5.21 %, with watermelon lowest and Pashmak highest (Mirshekari et al., 2023; Piri et al., 2025). How water consumption patterns captured through WF metrics relate to these broader sustainability indicators has not been explored, and combining the two could reveal new insight into how water use and sustainability connect.

Several gaps motivated this research. WF studies have proliferated for major staples and high-value horticultural crops in temperate and humid climates (Cao et al., 2021; Vanham et al., 2021), but far less has been done for specialty crops under hyperarid conditions. Most assessments examine individual crops in isolation, whereas comparing multiple related systems reveals relative performance and can inform crop selection (Karandish & Hoekstra, 2021). The grey water footprint, which captures the water quality impact of agrochemicals, has received insufficient attention in arid regions even though irrigation concentration effects may cause high pollution loading (Chukalla et al., 2020). Economic dimensions of water productivity are often overlooked, yet economic returns per unit of water matter enormously for farmer decisions and policy (Schyns et al., 2023). The integration of WF with emergy analysis has rarely been attempted and remains a promising frontier.

This study addresses these gaps through a comprehensive WF assessment of five jalizi crop systems in Sistan. The objectives are to (1) quantify blue, green, and grey water footprints for Gandak, Sefidak, Pashmak, watermelon, and melon from primary data covering 277 farms; (2) evaluate physical and economic water productivity in order to identify water-efficient and economically optimal alternatives; (3) analyze the relationships between WF metrics and emergy-derived sustainability indicators; (4) assess the water scarcity-weighted environmental burden given the extreme stress in Sistan; and (5) develop evidence-based recommendations for improving water sustainability through crop selection, irrigation technology, and nutrient management.

Five hypotheses were tested. (H1) Pashmak, with its shorter growing season and early harvest, shows a

significantly lower total WF than full-season crops. (H2) The blue water footprint dominates across all systems given minimal rainfall and near-total irrigation dependence. (H3) The grey water footprint varies substantially among systems in proportion to nitrogen fertilizer intensity. (H4) A negative correlation appears between total WF and emergy renewability, which would indicate that water-intensive systems have lower ecological sustainability. (H5) Economic water productivity rankings differ from physical rankings because of price differences, which creates potential trade-offs between water conservation and farm profitability.

This work contributes in several ways. Methodologically, it advances WF–emergy integration and demonstrates the complementarity of water-specific and comprehensive environmental accounting. Empirically, it is the first systematic WF assessment for jalizi crops in a hyperarid region and so expands the geographic and climatic coverage of the literature. Practically, the findings inform crop selection strategies, irrigation technology priorities, and nutrient management suited to water-scarce conditions. The study also speaks to broader debates about sustainable intensification in arid regions, where conflicts between production, livelihoods, and resource sustainability continue to sharpen (Grafton et al., 2020). As climate change worsens water scarcity globally, lessons from Sistan, an extreme case, offer insight for agricultural adaptation elsewhere.

1.1. Water footprint concept and applications

The water footprint concept was formalized by Hoekstra (2003) and standardized through the Water Footprint Assessment Manual (Hoekstra et al., 2021). It provides spatially and temporally explicit accounting of water consumption and pollution across product supply chains, and distinguishes three components: the blue water footprint (consumption of surface water and groundwater through evapotranspiration or product incorporation), the green water footprint (rainwater stored in soil and consumed through evapotranspiration), and the grey water footprint (the freshwater volume required to dilute pollutants to meet water quality standards). This breakdown helps to identify water source dependencies, pollution hotspots, and the points at which intervention would matter most. Recent refinements include water scarcity weighting for regional availability (Hoekstra et al., 2023) and integration with life cycle assessment (Jefferies et al., 2022).

1.2. Emergy analysis and sustainability assessment

Emergy analysis quantifies all energy inputs to a system in solar emergy units (solar emjoules), covering both renewable environmental inputs and purchased economic inputs. Its key indicators are emergy renewability (%R), the emergy yield ratio (EYR), the

environmental loading ratio (ELR), and the environmental sustainability index (ESI). Applied to agricultural systems, these enable evaluation of environmental support requirements, resource use efficiency, and long-term sustainability (Giannetti et al., 2020; Yang et al., 2021). Combining emergy with water footprint assessment is an emerging direction in sustainability science that may reveal synergies and trade-offs between water conservation and broader environmental goals.

2. Materials and Methods

2.1. Study area description

The Sistan plain encompasses approximately 15,697 km² in northern Sistan and Baluchistan Province, southeastern Iran (30°12' to 31°28' N; 61°16' to 61°50' E). The region has a Köppen BWh climate classification (hot desert) with extreme aridity. Its mean annual temperature is 21.5 °C (2 °C in winter and 45 °C in summer), mean annual precipitation is 54 mm, potential evapotranspiration exceeds 4,000 mm per year, reference evapotranspiration reaches 8–12 mm per day in summer, and the aridity index of 0.013 places the plain in the extreme hyperarid class.

2.2. Sampling design

Sample sizes were determined using the formula of Cochran (1977) for finite populations,

$$n = \frac{Z^2 \times p \times q / d^2}{1 + [(Z^2 \times p \times q) / (N \times d^2)]} \quad (1)$$

where n is the required sample size, $Z = 1.96$ at the 95 % confidence level, $p = 0.5$ represents maximum variability, $q = 1 - p = 0.5$, $d = 0.05$ is the margin of error, and N is the total population size. The resulting sample sizes were 45 farms for Gandak, 53 for Sefidak, 37 for Pashmak, 60 for watermelon and 82 for melon, giving a total of 277 farms.

2.3. Water footprint calculations

2.4. Total water footprint

The total water footprint comprises three components,

$$WF_{total} = WF_{blue} + WF_{green} + WF_{grey} \quad (2)$$

where WF_{total} , WF_{blue} , WF_{green} and WF_{grey} are the total, blue, green and grey water footprints, respectively (m³ ton⁻¹).

2.5. Blue water footprint

The blue water footprint represents irrigation water consumption,

$$WF_{blue} = CWU_{blue} / Y \quad (3)$$

where CWU_{blue} is blue crop water use (m³ ha⁻¹) and Y is crop yield (ton ha⁻¹). Blue crop water use is

$$CWU_{blue} = Irrigation_{applied} \times (1 - Return_{flow\ fraction}) \quad (4)$$

with a return flow fraction of 0.15. The irrigation applied is

$$Irrigation_{applied} = n_{events} \times Application_{rate} \times Field_{area} \quad (5)$$

where n_{events} is the number of irrigation events and the application rate is the water applied per event: 1,200–1,500 m³ ha⁻¹ for basin irrigation, 800–1,000 m³ ha⁻¹ for furrow irrigation, and 250–350 m³ ha⁻¹ for drip irrigation.

2.6. Green water footprint

The green water footprint represents rainfall consumption,

$$WF_{green} = CWU_{green} / Y \quad (6)$$

where CWU_{green} is green crop water use (m³ ha⁻¹), obtained from

$$CWU_{green} = 10 \times \sum(P_{eff}) \quad (7)$$

in which 10 converts millimetres to m³ ha⁻¹ and $\sum(P_{eff})$ is the sum of effective precipitation (mm). Effective precipitation was estimated with the USDA SCS method,

$$P_{eff} = P_{total} \times (125 - 0.2 \times P_{total}) / 125 \quad (8)$$

where P_{total} is total precipitation (mm).

2.7. Grey water footprint

The grey water footprint quantifies nitrogen pollution,

$$WF_{grey} = (AR \times \alpha) / (C_{max} - C_{nat}) / Y \quad (9)$$

where AR is the nitrogen application rate (kg N ha⁻¹), $\alpha = 0.10$ is the leaching fraction, $C_{max} = 0.010$ kg m⁻³ is the maximum acceptable concentration, and $C_{nat} = 0.001$ kg m⁻³ is the natural background concentration. The nitrogen load is

$$L_N = AR_N \times \alpha \quad (10)$$

where L_N is the nitrogen load (kg N ha⁻¹). Nitrogen application rates were 950 kg N ha⁻¹ for Gandak, 1,050 for Sefidak, 100 for Pashmak, 950 for watermelon and 950 for melon.

2.8. Water productivity indicators

Physical water productivity was calculated as

$$WP_{phys} = Y / (CWU_{blue} + CWU_{green}) = 1000 / WF_{total} \quad (11)$$

where WP_{phys} is expressed in kg m⁻³, and economic water productivity as

$$WP_{econ} = (P \times 1000) / WF_{total} \quad (12)$$

where WP_{econ} is in Toman m⁻³ and P is the farm-gate price (Toman kg⁻¹). Farm-gate prices in 2020 were 18,350 Toman kg⁻¹ for Gandak, 16,000 for Sefidak, 30,000 for Pashmak, 18,000 for watermelon and 18,350 for melon.

2.9. Water scarcity assessment

The scarcity-weighted water footprint was obtained from

$$WF_{scarcity} = WF_{total} \times WSI_{region} \quad (13)$$

where $WSI_{\text{region}} = 0.95$ for Sistan, which corresponds to extreme scarcity.

2.10. Emergy analysis integration

Four emergy indicators were used. Emergy renewability is

$$\%R = (R_{\text{emergy}}/U_{\text{total}}) \times 100 \quad (14)$$

the emergy yield ratio is

$$EYR = U_{\text{total}}/F_{\text{purchased}} \quad (15)$$

the environmental loading ratio is

$$ELR = (N_{\text{emergy}} + F_{\text{purchased}})/R_{\text{emergy}} \quad (16)$$

and the environmental sustainability index is

$$ESI = EYR/ELR \quad (17)$$

2.11. Economic analysis

The gross value of production (million Toman ha^{-1}) is

$$GVP = Y \times P \quad (18)$$

the total cost of production (million Toman ha^{-1}) is

$$TCP = \sum(C_{\text{inputs}}) + C_{\text{labor}} + C_{\text{machinery}} + C_{\text{land}} \quad (19)$$

net revenue (million Toman ha^{-1}) is

$$NR = GVP - TCP \quad (20)$$

and the benefit-cost ratio is

$$B/C = GVP/TCP \quad (21)$$

2.12. Statistical analysis

Differences among systems were tested with a one-way analysis of variance,

$$Y_{ij} = \mu + \tau_i + \varepsilon_{ij} \quad (22)$$

where Y_{ij} is the observed value, μ the overall mean, τ_i the treatment effect and ε_{ij} the random error, at a significance level of $\alpha = 0.05$. Associations were quantified with the Pearson correlation coefficient,

$$r = \frac{\sum[(X_i - \bar{X})(Y_i - \bar{Y})]}{\sqrt{\sum(X_i - \bar{X})^2 \times \sum(Y_i - \bar{Y})^2}} \quad (23)$$

where r ranges from -1 to $+1$, and dispersion with the coefficient of variation,

$$CV = (SD/Mean) \times 100 \quad (24)$$

where CV is expressed as a percentage and SD is the standard deviation.

3. Results

3.1. Descriptive statistics of production systems

Table 1 presents descriptive statistics for the five jalizi crop production systems studied in the Sistan region during the 2020 growing season, covering 277 farms in total. All crops except Pashmak achieved similar yields of around 25 ton ha^{-1} . Pashmak yielded $14.0 \pm 1.5 \text{ ton ha}^{-1}$ because it is harvested early, before physiological maturity, typically 30–45 days after planting.

Table 1. Descriptive statistics of jalizi crop production systems in the Sistan region (mean $\pm$ standard deviation).

Crop system	Sample size (n)	Yield (ton ha^{-1})	Growing season (months)	Irrigation water ($\text{m}^3 \text{ ha}^{-1}$)	N fertilizer (kg ha^{-1})	Farm-gate price (Toman kg^{-1})
Gandak	45	25.0 ± 2.3	4.5	$8,500 \pm 650$	950	18,350
Sefidak	53	25.0 ± 2.8	4.5	$9,200 \pm 720$	1,050	16,000
Pashmak	37	14.0 ± 1.5	2.5	$6,000 \pm 480$	100	30,000
Watermelon	60	25.0 ± 3.2	5.5	$10,500 \pm 830$	950	18,000
Melon	82	25.0 ± 2.6	4.5	$8,500 \pm 670$	950	18,350
Mean	277 total	22.8 ± 5.2	4.3 ± 1.1	$8,540 \pm 1,520$	800 ± 390	$20,140 \pm 5,680$

Irrigation water application ranged from $6,000 \text{ m}^3 \text{ ha}^{-1}$ (Pashmak) to $10,500 \text{ m}^3 \text{ ha}^{-1}$ (watermelon), and nitrogen fertilizer application from 100 kg ha^{-1} (Pashmak) to $1,050 \text{ kg ha}^{-1}$ (Sefidak). Pashmak commanded the highest price ($30,000 \text{ Toman kg}^{-1}$) and Sefidak the lowest ($16,000 \text{ Toman kg}^{-1}$).

3.2. Water footprint components

Table 2. Water footprint components for the five jalizi crop production systems in the Sistan region.

Crop system	Blue WF ($\text{m}^3 \text{ ton}^{-1}$)	Green WF ($\text{m}^3 \text{ ton}^{-1}$)	Grey WF ($\text{m}^3 \text{ ton}^{-1}$)	Total WF ($\text{m}^3 \text{ ton}^{-1}$)	Rank
Gandak	340.0 (44.3 %)	5.67 (0.7 %)	422.2 (55.0 %)	767.9	2
Sefidak	368.0 (43.8 %)	5.67 (0.7 %)	466.7 (55.5 %)	840.3	4
Pashmak	428.6 (83.5 %)	5.62 (1.1 %)	79.4 (15.5 %)	513.6	1
Watermelon	420.0 (49.5 %)	6.93 (0.8 %)	422.2 (49.7 %)	849.2	5
Melon	340.0 (44.3 %)	5.67 (0.7 %)	422.2 (55.0 %)	767.9	2
Mean $\pm$ SD	379.3 ± 41.7	5.91 ± 0.57	362.5 ± 160.1	747.8 ± 136.5	–

The grey water footprint ranged from $79.4 \text{ m}^3 \text{ ton}^{-1}$ (Pashmak) to $466.7 \text{ m}^3 \text{ ton}^{-1}$ (Sefidak), a 5.9-fold

The blue water footprint ranged from $340.0 \text{ m}^3 \text{ ton}^{-1}$ (Gandak and melon) to $428.6 \text{ m}^3 \text{ ton}^{-1}$ (Pashmak), with a coefficient of variation of 11.2 %. The mean across all systems was $379.3 \pm 41.7 \text{ m}^3 \text{ ton}^{-1}$ (Table 2). The green water footprint ranged from $5.62 \text{ m}^3 \text{ ton}^{-1}$ (Pashmak) to $6.93 \text{ m}^3 \text{ ton}^{-1}$ (watermelon), contributed less than 1.1 % in every system, and averaged $5.91 \pm 0.57 \text{ m}^3 \text{ ton}^{-1}$.

difference. It contributed 49.7–55.5 % of the total water footprint for Gandak, Sefidak, watermelon and melon,

but only 15.5 % for Pashmak, and averaged $362.5 \pm 160.1 \text{ m}^3 \text{ ton}^{-1}$.

Total water footprint ranged from $513.6 \text{ m}^3 \text{ ton}^{-1}$ (Pashmak) to $849.2 \text{ m}^3 \text{ ton}^{-1}$ (watermelon), a variation of 65.4 % among systems. The Pashmak total was 31.3 % below the mean of $747.8 \text{ m}^3 \text{ ton}^{-1}$, while watermelon and Sefidak showed the highest totals (13.6 % and 12.4 % above the mean, respectively). The coefficient of variation was 18.25 %.

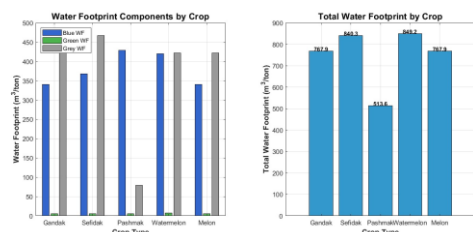


Figure 1. Water footprint components (blue, green, grey) for each crop system. Blue WF ranged from 340 to $429 \text{ m}^3 \text{ ton}^{-1}$, green WF appeared as minimal bars ($< 7 \text{ m}^3 \text{ ton}^{-1}$), and grey WF varied from $79 \text{ m}^3 \text{ ton}^{-1}$ (Pashmak) to $467 \text{ m}^3 \text{ ton}^{-1}$ (Sefidak).

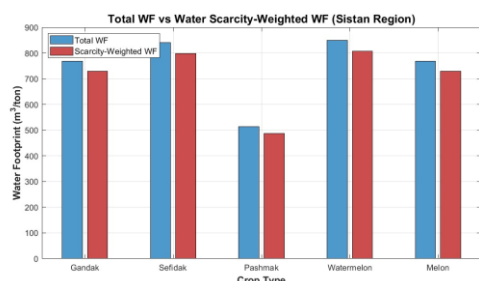


Figure 2. Total water footprint across crops: Pashmak 513.6, Gandak 767.9, melon 767.9, Sefidak 840.3 and watermelon $849.2 \text{ m}^3 \text{ ton}^{-1}$.

Table 3. Physical and economic water productivity of the jalizi crop systems, with deviations from the mean.

Crop system	Physical WP (kg m^{-3})	Deviation from mean (%)	Economic WP (1000 Toman m^{-3})	Deviation from mean (%)	Rank (economic)
Gandak	1.302	-5.9	23.9	-18.4	2
Sefidak	1.190	-14.0	19.0	-35.1	5
Pashmak	1.947	+40.7	58.4	+99.5	1
Watermelon	1.178	-14.9	21.2	-27.6	4
Melon	1.302	-5.9	23.9	-18.4	2
Mean $\pm$ SD	1.384 ± 0.321	—	29.3 ± 14.6	—	—

Economic water productivity ranged from 19.0 thousand Toman m^{-3} (Sefidak) to 58.4 thousand Toman m^{-3} (Pashmak), a difference of 207 %. The mean was 29.3 ± 14.6 thousand Toman m^{-3} ; Pashmak was 99.5 % above it and Sefidak 35.1 % below it, with a coefficient of variation of 49.8 %.

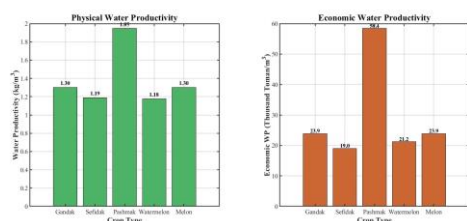


Figure 4. Physical water productivity (kg m^{-3}) and economic water productivity (thousand Toman m^{-3}) across crops.

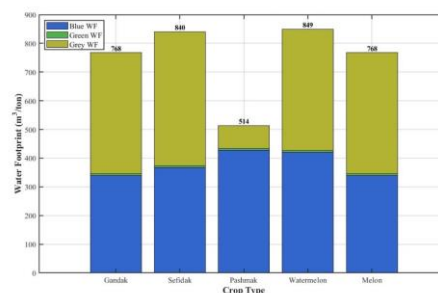


Figure 3. Stacked water footprint components showing the proportional contribution of the blue, green and grey components to the total.

3.3. Water productivity metrics

Physical water productivity ranged from 1.178 kg m^{-3} (watermelon) to 1.947 kg m^{-3} (Pashmak), a difference of 65.3 % (Table 3). The mean was $1.384 \pm 0.321 \text{ kg m}^{-3}$; Pashmak was 40.7 % above it and watermelon 14.9 % below it, with a coefficient of variation of 23.2 %.

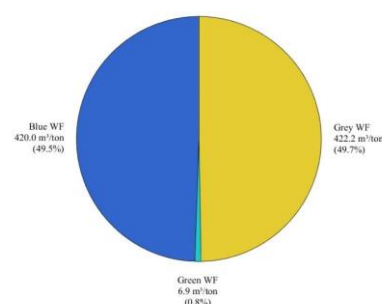


Figure 5. Water footprint components for watermelon: blue WF 49.5 % ($420.0 \text{ m}^3 \text{ ton}^{-1}$), grey WF 49.7 % ($422.2 \text{ m}^3 \text{ ton}^{-1}$) and green WF 0.8 % ($6.93 \text{ m}^3 \text{ ton}^{-1}$).

3.4. Water scarcity-weighted water footprint

The scarcity-weighted water footprint was calculated using a Water Scarcity Index of 0.95 for Sistan (Table 4)

and ranged from 487.9 m³ ton⁻¹ (Pashmak) to 806.7 m³ ton⁻¹ (watermelon).

Table 4. Water scarcity-weighted footprint and regional water use estimates (7,000 hectares cultivated).

Crop system	Total WF (m ³ ton ⁻¹)	WF _{scarcity} (m ³ ton ⁻¹)	Environmental pressure class	Annual regional water use (million m ³)
Gandak	767.9	729.5	High	~12–15
Sefidak	840.3	798.3	Very high	~13–16
Pashmak	513.6	487.9	Moderate–high	~4–5
Watermelon	849.2	806.7	Very high	~15–18
Melon	767.9	729.5	High	~12–15
Weighted mean	747.8	710.4	High	~60–70 total

Estimated annual regional water use for jalizi crops was 60–70 million m³, which represented 6–7 % of total agricultural water use in Sistan while occupying less than 1 % of the cultivated area.

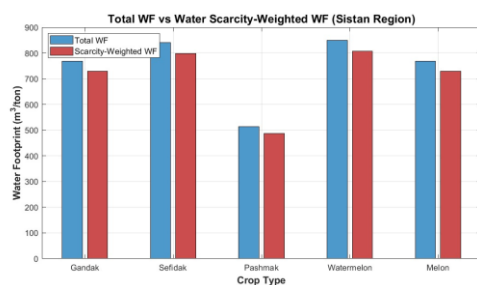


Figure 6. Comparison of the conventional total water footprint and the scarcity-weighted water footprint across crops.

Table 5. Pearson correlation coefficients between water footprint and energy sustainability indicators.

Relationship	Pearson <i>r</i>	<i>r</i> ² (variance explained)	<i>p</i> -value	Significance	Interpretation
Total WF vs. energy renewability	−0.955	0.912 (91.2 %)	0.011		Strong negative
Total WF vs. EYR	−0.537	0.288 (28.8 %)	0.351	NS	Weak negative
Total WF vs. ELR	−0.483	0.233 (23.3 %)	0.411	NS	Weak negative
Physical WP vs. %R	+0.932	0.869 (86.9 %)	0.020		Strong positive
Grey WF vs. ELR	+0.678	0.460 (46.0 %)	0.208	NS	Moderate positive

significant *ap* < 0.05; * significant at *p* < 0.05; NS = not significant.

Total water footprint and the energy yield ratio showed a weak negative correlation ($r = -0.537$, $p = 0.351$), as did total water footprint and the environmental loading ratio ($r = -0.483$, $p = 0.411$).

Grey water footprint and the environmental loading ratio showed a moderate positive correlation ($r = +0.678$, $p = 0.208$).

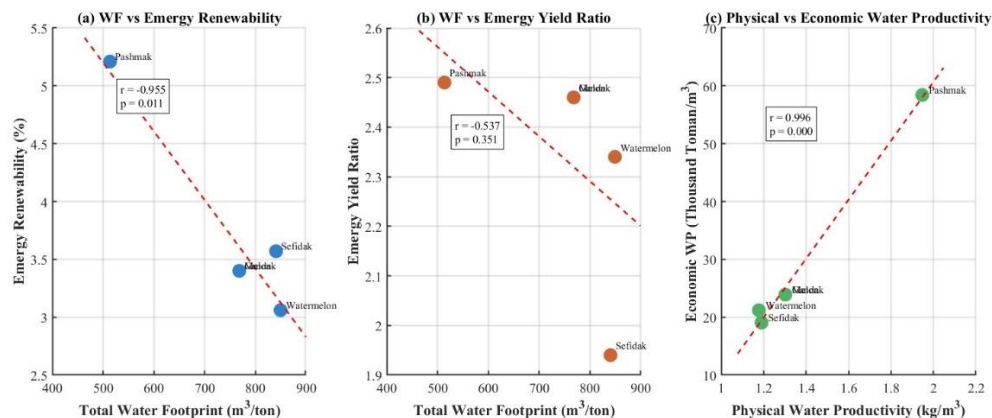


Figure 7. Correlation analysis between water footprint and sustainability indicators. Panel A: total WF against energy renewability ($r = -0.955$, $p = 0.011$). Panel B: total WF against EYR ($r = -0.537$, $p = 0.351$). Panel C: physical against economic water productivity.

3.6. Economic performance analysis

Table 6 presents the economic performance indicators. The gross value of production ranged from 400.0 million Toman ha⁻¹ (Sefidak) to 458.8 million Toman ha⁻¹ (Gandak and melon), with a coefficient of

variation of 5.9 %. Total costs of production ranged from 7.5 million Toman ha⁻¹ (Pashmak) to 16.0 million Toman ha⁻¹ for the other systems, so that the Pashmak cost was 53 % lower than the rest.

Table 6. Economic performance indicators for the jalizi crop production systems (M = million Toman).

Crop system	GVP (M Toman ha ⁻¹)	TCP (M Toman ha ⁻¹)	Net revenue (M Toman ha ⁻¹)	B/C ratio	Rank (profitability)
Gandak	458.8	16.0	442.8	28.7	2
Sefidak	400.0	16.0	384.0	25.0	5
Pashmak	420.0	7.5	412.5	56.0	1
Watermelon	450.0	16.0	434.0	28.1	3
Melon	458.8	16.0	442.8	28.7	2
Mean ± SD	437.5 ± 25.8	14.3 ± 3.8	423.2 ± 25.2	33.3 ± 12.9	–

Net revenue ranged from 384.0 million Toman ha⁻¹ (Sefidak) to 442.8 million Toman ha⁻¹ (Gandak and melon). The benefit-cost ratio ranged from 25.0

(Sefidak) to 56.0 (Pashmak), so that the Pashmak ratio was nearly double that of the next-highest systems, Gandak and melon at 28.7.

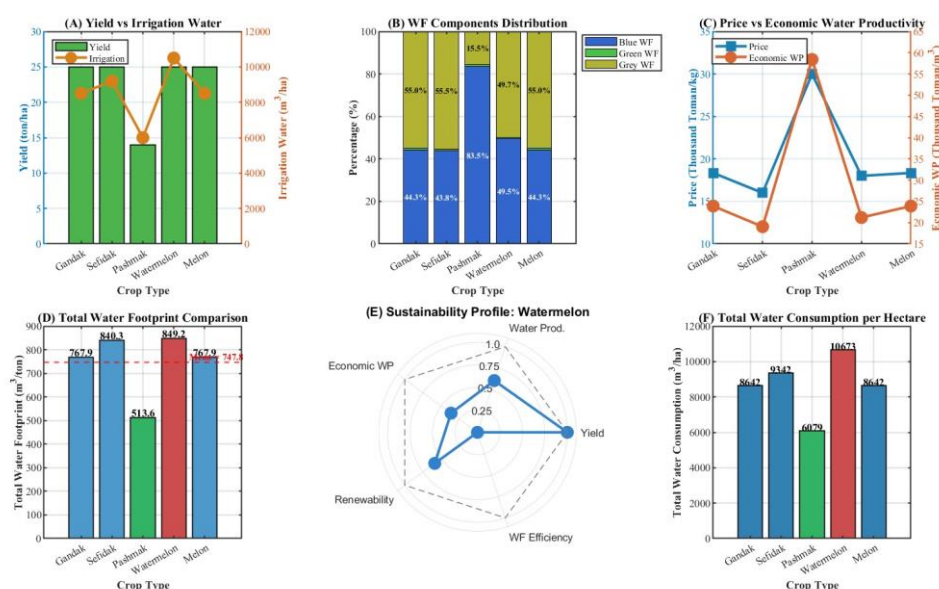


Figure 8. Comprehensive comparative analysis. Panel A: yield against irrigation water. Panel B: water footprint component distribution. Panel C: price against economic water productivity. Panel D: total water footprint comparison. Panel E: sustainability radar chart for watermelon. Panel F: total water use per hectare.

3.7. Analysis of variance

One-way analysis of variance tested the differences among the five crop systems (Table 7). Blue water footprint differed significantly among systems ($F = 8.42$, $p = 0.003$), as did grey water footprint ($F = 156.73$, $p < 0.001$), total water footprint ($F = 24.56$, $p < 0.001$), physical water productivity ($F = 18.91$, $p < 0.001$), economic water productivity ($F = 42.33$, $p < 0.001$) and net revenue ($F = 12.67$, $p < 0.001$). Green water footprint did not differ significantly ($F = 0.18$, $p = 0.945$).

0.001), total water footprint ($F = 24.56$, $p < 0.001$), physical water productivity ($F = 18.91$, $p < 0.001$), economic water productivity ($F = 42.33$, $p < 0.001$) and net revenue ($F = 12.67$, $p < 0.001$). Green water footprint did not differ significantly ($F = 0.18$, $p = 0.945$).

Table 7. One-way analysis of variance testing differences among the five jalizi crop systems.

Variable	F-statistic	p-value	Significance	Interpretation
Blue WF	8.42	0.003		Highly significant difference
Green WF	0.18	0.945	NS	No significant difference
Grey WF	156.73	< 0.001		Extremely significant difference
Total WF	24.56	< 0.001		Extremely significant difference
Physical WP	18.91	< 0.001		Extremely significant difference
Economic WP	42.33	< 0.001		Extremely significant difference
Net revenue	12.67	< 0.001		Extremely significant difference

$p < 0.001$; ** $p < 0.01$; NS = not significant.

Post-hoc Tukey HSD tests showed that Pashmak differed significantly ($p < 0.05$) from all other systems for grey water footprint, total water footprint, physical

water productivity and economic water productivity. Gandak, Sefidak, watermelon and melon formed homogeneous subgroups for most variables.

4. Discussion

The total water footprint values found here (514–849 $\text{m}^3 \text{ ton}^{-1}$) substantially exceed global averages for cucurbits. Mekonnen and Hoekstra (2020) reported 235 $\text{m}^3 \text{ ton}^{-1}$ for watermelon and 180 $\text{m}^3 \text{ ton}^{-1}$ for melon, so the present values are 2.8–4.7 times higher. Four factors explain the discrepancy: the extreme hyperaridity of Sistan, with only 54 mm of annual rainfall against more than 4,000 mm of potential evapotranspiration; surface irrigation systems operating at 40–50 % efficiency compared with the 85–95 % achieved by drip systems elsewhere; a near-zero rainfall contribution (0.7–1.1 % of total WF) against 35–75 % green water in humid regions; and excessive nitrogen application (950–1,050 kg ha^{-1} against a recommended 150–250 kg ha^{-1}), which generates an elevated grey water footprint.

Comparison with other arid region studies, including Iran's Central Plateau (320–680 $\text{m}^3 \text{ ton}^{-1}$), Saudi Arabia and Pakistan's Indus Basin (450–750 $\text{m}^3 \text{ ton}^{-1}$), indicates that the Sistan values fall within the expected range for comparable water-limited conditions. Jalizi crops are therefore not inherently high-footprint products; the extreme climate and the management practices drive the elevated consumption.

Pashmak performed best across multiple sustainability dimensions: the lowest total water footprint (33–39 % below the other systems), the highest physical and economic water productivity, the highest energy renewability (5.21 %), and the best benefit-cost ratio (56.0). Its abbreviated growing season strategy, with harvest 30–45 days after planting, reduces irrigation to 6,000 $\text{m}^3 \text{ ha}^{-1}$ against 8,500–10,500 for the other crops, minimizes fertilizer requirements to 100 kg N ha^{-1} , captures premium seasonal pricing (30,000 Toman kg^{-1}), and creates opportunities for double cropping.

The strong negative correlation between total water footprint and energy renewability ($r = -0.955$, $p = 0.011$) is a novel empirical finding. Water-intensive production systems also exhibit lower ecological sustainability, most likely because high-water systems require more purchased inputs, which carry low renewability in energy accounting. This result validates the complementarity of the water footprint and energy approaches and suggests that water conservation strategies yield co-benefits for overall system sustainability.

Three primary intervention pathways emerge. Upgrading irrigation technology through conversion to drip could reduce the blue water footprint by 45–50 % with an economic payback period of 5–8 years including government subsidies. Precision nutrient management through soil testing, split applications and reduced nitrogen rates, from 950–1,050 to 200–300 kg ha^{-1} , could decrease the grey water footprint by 60–70 % while saving 2.1–2.8 million Toman ha^{-1} annually. Adaptive crop selection that prioritizes Pashmak during

years of severe scarcity could save 14–17.5 million m^3 regionally.

The economic analysis reveals only partial alignment between water sustainability and farm profitability. Pashmak represents a win-win case and Sefidak a lose-lose one, while Gandak, melon and watermelon create tension between maximizing per-hectare profit and improving water efficiency, because current water pricing fails to internalize scarcity costs. Policy responses should include volumetric water pricing with tiered rates that reflect scarcity, capital subsidies of 40–50 % for drip irrigation adoption, market development for water-efficient products, and strengthened extension services. Revenue from water pricing could fund the technology subsidies and create a self-financing system, implemented gradually over 5–7 years to allow farmers to adapt.

5. Conclusions

This study presents the first comprehensive water footprint assessment of jalizi crop production systems in Iran's water-scarce Sistan region, analyzing data from 277 farms across five production systems: Gandak, Sefidak, Pashmak, watermelon and melon. Total water footprint varied substantially, from 513.6 $\text{m}^3 \text{ ton}^{-1}$ for Pashmak to 849.2 $\text{m}^3 \text{ ton}^{-1}$ for watermelon, a variation of 65 % that represents a significant opportunity for water conservation through strategic crop selection.

The blue water footprint dominated all systems, contributing 43.8–83.5 % of total consumption because of the near-complete dependence on irrigation in a hyperarid climate that receives only 54 mm of rain a year. The grey water footprint arising from over-application of nitrogen fertilizer represented 15.5–55.5 % of the total, which identifies fertilizer management as a critical intervention point.

Pashmak emerged as the most water-efficient system, with the highest physical water productivity (1.95 kg m^{-3}) and economic water productivity (58,416 Toman m^{-3}), attributable to its abbreviated 2.5-month growing season, which minimizes irrigation and fertilizer inputs while commanding premium market prices. The strong negative correlation between total water footprint and energy renewability ($r = -0.955$, $p = 0.011$) validated the complementarity of the two assessment approaches and indicates that water-intensive production systems also exhibit lower ecological sustainability.

Three primary intervention pathways were identified: adoption of drip irrigation could reduce the blue water footprint by 45–50 %, precision nitrogen management could decrease the grey water footprint by 60–70 %, and adaptive crop selection based on seasonal water availability could optimize regional water allocation. Implemented together, these could achieve a 50–60 % reduction in total water footprint and bring the jalizi crops of Sistan close to global averages despite the extreme climatic constraints.

Policy recommendations include tiered volumetric water pricing, incentives for technology adoption, market development for water-efficient products, and strengthened extension services for precision agriculture, so that farmer incentives are aligned with sustainable water resource management in this critically water-stressed region.

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Conflict of interest

The author declares no conflict of interest related to this research.

Data availability

The datasets supporting the findings of this study are available from the corresponding author upon reasonable request, subject to farmer privacy protections.

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