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Virtual water trade: Economic development and independence through optimal allocation

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ABSTRACT

The uneven temporal and spatial distribution of water has led to water crises in many countries. The virtual water trade constitutes a means of dealing with such crises. The virtual water trade uncovers the hidden flow of water in traded commodities between countries. This work proposes a multi-objective optimization model that maximizes the revenue and minimizes the direct and indirect water uses of producing strategic agricultural and industrial goods. Several water prices and levels of subsidies are accounted for in the optimization. A country's agricultural and industrial independence is used to constraint the optimization problem, which achieves food security and economic benefit. The proposed optimization model is applied to identify the portfolio of suitable agricultural products in Iran. Results show that wheat features the largest portion of water use in the agricultural sector, while potatoes and tomatoes are more lucrative due to their relative high price and low water use of about 400 m^3 per ton of produce. Moreover, it is found that raising the water price reduces industrial imports because producing industrial goods is cost-effective in offsetting the reduction of net-revenue from agricultural production.

1. Introduction

The provision of safe and reliable access to adequate clean water is a key challenge in many countries (Grey and Sadoff, 2007). Population growth has boosted the energy and food use, and industrialization and urbanization have further depleted water resources (Vörösmarty et al., 2000; Molden and de Fraiture, 2010). Climate, and, in turn water resources, have been affected by natural and anthropogenic forces, which have exacerbated the uneven distribution of water between and within countries. These issues have been tackled with engineering works, such as the building of infrastructure, dams, and aqueducts for storing and conveying water to alleviate water shortages. These solutions, however, usually offer temporary relief instead of targeting the root causes. Virtual water trade provides a new approach to reveal and exploit the hidden flow of water and the water used to produce energy, food, and commodities (Abdelkader et al., 2018).

Virtual water is the total amount of water consumed during the process of producing services and goods (Allan, 1993; Hoekstra, 2003; Hoekstra, and Mekonnen, 2012). International trade indirectly moves a large volume of water among countries. The global redistribution of water occurs through traded products, which may contain large volumes of embodied water (Hoekstra, 2011; Zhang et al., 2016). The virtual water flow is a method to balance the distribution of water between water-rich and water-scarce areas (Zhi et al., 2018; Qu et al., 2017).

The virtual water trade idea has applied of several purposes, such as the monitoring of trade parameters (e.g., imports and exports) between regions (e.g., Sun et al., 2016; Chouchane et al., 2017; Bae and Dall'erba, 2018; Wahba et al., 2018), evaluating food crises (Tamea et al., 2016), and risk assessment (Qu et al., 2017), relying on input-output analysis methods. Jiang et al. (2015) developed a multi-regional input-output model for China, and reported that some of China's provinces, despite their low water availability, export a significant amount of water indirectly. The latter authors recommended that developing a market-based water pricing system and enhancing water systems' efficiency can prevent unsustainable production and exports, and redistributes water among provinces.

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Table 1
Review of virtual water trade studies.

Authors	Location of study	Goal and Method	Key findings
Dalin et al. (2014)	China	Optimization of interprovincial food trade	Analyzing the virtual water flow patterns and the corresponding water savings. They found that China's domestic food trade was efficient in terms of rainwater but inefficient regarding irrigation.
Tamea et al. (2016)	Argentina	Food crisis and virtual water assessment	Determining the vulnerability of countries by estimating the amount of food they exported and imported to Argentina, and the food produced in each country.
Sun et al. (2016)	China	Monitoring Virtual water trade of cereal and grain	Surveying the water pressure index by assessing different regions of China, as well as the volume of exports and imports. Recommended that China should focus on water saving policies as well as boosting water use efficiency in order to prevent future food crises.
Qu et al. (2017)	Global Trade System	Risk evaluation of Virtual water trade	A snapshot of the vulnerability in the global economy was drawn, but how the environmental or local factors could distort production was not considered.
Chouchane et al. (2017)	Tunisia	Monitoring Virtual water trade by input-output method	Different regression models for different plants were implemented and eventually importing the plants with high water use instead of producing them was recommended.
Wang et al. (2017)	China	Water price optimization	A proposed system was introduced as an effective solution for increasing water allocation efficiency, which in agriculture leads to increasing water use efficiency and consequently reducing agricultural production.
Bae and Dall'erba (2018)	Arizona	Monitoring Virtual water trade with the input-output method	Three different scenarios were developed with the aim of saving 19% more water as follows: 1. Increased irrigation efficiency, 2. Increased water prices, 3. Reduce exports, with the first scenario being the best.
Wahba et al. (2018)	Egypt	Monitoring Virtual water trade by input-output method	Imports, exports, and estimated household water uses were calculated to monitor the virtual water trade of Egypt.
Wang et al. (2019)	China	Monitoring Virtual water trade of cereal and grain	The present situation of China is inappropriate for cereal exports, and the virtual water from this trade equals 1179.24 billion cubic meters a year.

A large number of preceding virtual water studies have focused on monitoring the amount of virtual water in trades, and a few of them optimized the trading system (Table 1). These studies have been centered round the agricultural trades, but the tradeoff between economic benefits of agricultural and industrial commodities and their associated water use rates have been often neglected. Some of these studies have considered water pricing as one of the effective ways to manage water resources (e.g., Wang et al., 2017; Bae and Dall'erba, 2018). This study proposes the joint management of agricultural and industrial production to guarantee a country's independence and the security of water resources.

Iran is considered as the case study for this research due to its severe water stress and lack of management with respect to the virtual water trade (Bozorg-Haddad, 2018). Moreover, Iran's government subsidizes water, which renders the price of water being lower than its actual cost. This research addresses current gaps in virtual water trade research by offering a new method to optimize the virtual water trade that redistributes water to enhance economic development and independence. This paper presents a novel multi-objective optimization model that integrates agricultural and industrial virtual water trade under gradual increases of the water price by means of a production security constraint.

2. Methods

This work presents a method to optimize virtual water trade considering two objectives. The first objective is the minimization of the virtual water use, and the second one is the maximization of revenue. The multi-objective Non-Dominated Sorting Genetic (NSGA)-II algorithm is applied for optimization in this work (Reed et al., 2003; Tang et al., 2007). The Nash bargaining method is implemented for choosing a solution among those in the Pareto front. Fig. (1) depicts the flowchart of this paper's methodology.

2.1. Optimization model

The two-objective optimization problem is presented in this section. The decision variables are the internal production, export, and import amounts for the all considered agricultural (i) and industrial (j) products (Table 1).

2.1.1. Minimizing virtual water use

The first objective minimizes the virtual water use. Eq. (1) shows the formulation of the first objective function.

$$Minimize.\sum_{i=1}^{m}VWC_iPC_i+\sum_{j=1}^{n}VWS_jPS_j+\sum_{U=1}^{O}\sum_{K=1}^{P}VWC_UEPC_{UK}+\sum_{L=1}^{G}\sum_{K=1}^{P}VWS_LEPS_{LK} -\sum_{U=1}^{O}\sum_{K=1}^{P}VWC_UIPC_{UK}-\sum_{L=1}^{G}\sum_{K=1}^{P}VWS_LIPS_{LK} \quad (1)$$

where PC_i = amount of internal production (production in the home country to meet the country's demands) of Agricultural Product i(tons), PS_j = the amount of internal production of industrial product j(tons), IPC_{UK} = the amount of crop U imported from country K(tons), IPS_{LK} = the amount of industrial product Limported from country K(tons), EPC_{UK} = the amount of exported production of agricultural product $U$to country K(tons), EPS_{LK} = the amount of exported industrial product $L$to country K(tons), VWC_i = the virtual water use of crop i (m^3/ton), VWS_j = the virtual water use of industrial product j (m^3/ton), VWC_U = the virtual water use of exported agricultural product U (m^3/ton), and VWS_L = the virtual water use of exported industrial product L (m^3/ton). The constraints associated with the first objective are:

- **Reliable supply**

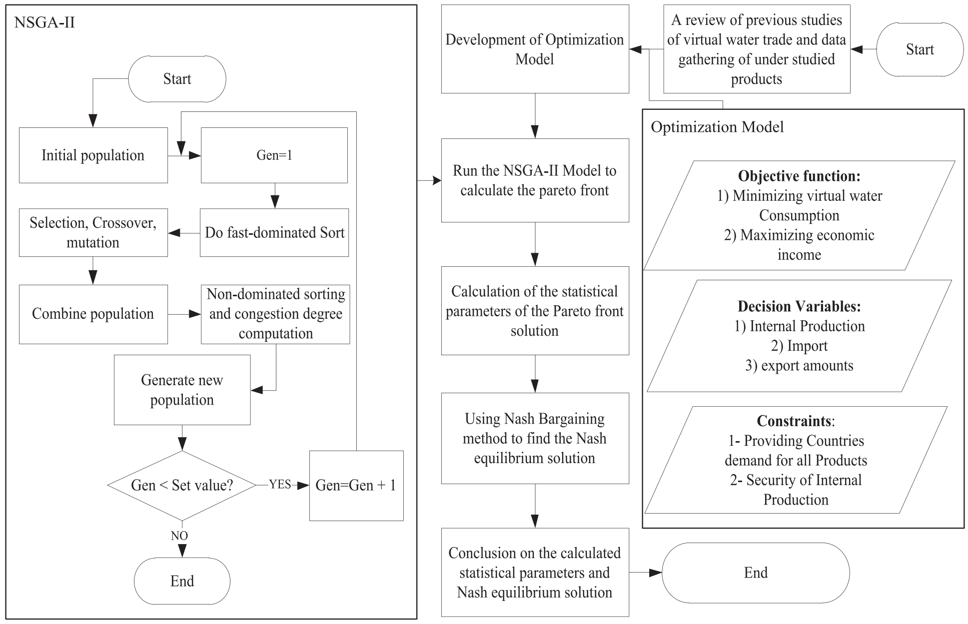

Fig. 1. Methodology's flowchart.

$$\sum_{i=1}^{m} PC_i + \sum_{j=1}^{n} PS_j + \sum_{U=1}^{O}\sum_{K=1}^{P} IPC_{UK} + \sum_{L=1}^{G}\sum_{K=1}^{P} IPS_{LK} - \sum_{U=1}^{O}\sum_{K=1}^{P} EPC_{UK} - \sum_{L=1}^{G}\sum_{K=1}^{P} EPS_{LK} \geq \sum_{i=1}^{m} DPC_i + \sum_{j=1}^{n} DPS_j \tag{2}$$

where DPC_i and DPS_j denote the country's demand for agricultural product i(tons) and for industrial product j(tons), respectively.

- **Net revenue larger than that of the baseline year**

$$\sum_{i=1}^{m} RB_i PC_i + \sum_{j=1}^{n} rb_j PS_j + \sum_{U=1}^{O}\sum_{K=1}^{P} RR_{UK} EPC_{UK} + \sum_{L=1}^{G}\sum_{K=1}^{P} rr_{LK} EPS_{LK} - \sum_{U=1}^{O}\sum_{K=1}^{P} RG_{UK} IPC_{UK} - \sum_{L=1}^{G}\sum_{K=1}^{P} rg_{LK} IPS_{LK} \geq A \tag{3}$$

where $RB_i =$ the unit revenue from the sale of agricultural product $i$in the country (dollars/ton), $rb_j =$ the unit revenue from the sale of industrial product $j$in the country (dollars/ton), $RR_{UK} =$ the unit revenue from exports of agricultural product U to country K(dollars/ton), $rr_{LK} =$ the unit revenue from exports of one industrial product L to country K(dollars/ton), $RG_{UK} =$ the import cost of one unit of agricultural product U from country K(dollars/ton), $rg_{LK} =$ the import cost of one unit of industrial product $L$from country K (dollars/ton), and $A =$ the annual net revenue from the sale of agricultural and industrial products of the country internally and by exports, which in this case is in 2018 dollars.

- **Security of internal production**

The following constraints ensure that the country produces at least 50% of its demand for agricultural and industrial products by internal production. This work provides security of internal production which compels the country to produce at least 50% of all the considered products' domestic demand. The cited percentage can be changed due to the country's specific conditions, and in some cases satisfaction of the internal demand of some products by importation may be economically justified.

$$\sum_{i=1}^{m} PC_i \geq \frac{\sum_{i=1}^{m} DPC_i}{2} \tag{4}$$

$$\sum_{j=1}^{n} PS_j \geq \frac{\sum_{j=1}^{n} DPS_j}{2} \tag{5}$$

2.1.2. *Maximizing net revenue*

The second objective maximizes the country's net revenue:

$$Maximize. \sum_{i=1}^{m} RB_i PC_i + \sum_{j=1}^{n} rb_j PS_j + \sum_{U=1}^{O}\sum_{K=1}^{P} RR_{UK} EPC_{UK} + \sum_{L=1}^{G}\sum_{K=1}^{P} rr_{LK} EPS_{LK} - \sum_{U=1}^{O}\sum_{K=1}^{P} RG_{UK} IPC_{UK} - \sum_{L=1}^{G}\sum_{K=1}^{P} rg_{LK} IPS_{LK} \tag{6}$$

The constraints associated with objective function (6) are:

- **Limits on the use of virtual water**

$$\sum_{i=1}^{m} VWC_i PC_i + \sum_{j=1}^{n} VWS_j PS_j + \sum_{U=1}^{O}\sum_{K=1}^{P} VWC_U EPC_{UK} + \sum_{L=1}^{G}\sum_{K=1}^{P} VWS_L EPS_{LK} - \sum_{U=1}^{O}\sum_{K=1}^{P} VWC_U IPC_{UK} - \sum_{L=1}^{G}\sum_{K=1}^{P} VWS_L IPS_{LK} \leq H \tag{7}$$

where Hdenotes the total annual volume of virtual water use in the baseline year 2018 (cubic meters).

The objective function (6) has two more constraints, i.e., supplying the country's demand as specified by Eq. (2) and safeguarding the independency and security of production according to Eqs. (4) and (5).

2.2. *The Non-Dominated Sorting Genetic Algorithm (NSGA)*

Goldberg (1989) proposed that multi-objective optimization problems can be solved using the Pareto ranking process, where, given the relative dominance of possible solutions, each member of the population is assigned a relative rank. This process, known as non-dominated

Table 2
Specification of developed scenarios.

Specification Scenario	Objectives	Decision variables	Water Price (Cents/ m^3)	Independence and security of production constraint
1	Maximizing economic income Minimizing virtual water use	Internal product, Export and Import	5	×
2	Maximizing economic income Minimizing virtual water use	Internal product, Export and Import	10	×
3	Maximizing economic income Minimizing virtual water use	Internal product, Export and Import	15	×
4	Maximizing economic income Minimizing virtual water use	Internal product, Export and Import	20	×
5	Maximizing economic income Minimizing virtual water use	Internal product, Export and Import	25	×
6	Maximizing economic income Minimizing virtual water use	Internal product, Export and Import	5	✓
7	Maximizing economic income Minimizing virtual water use	Internal product, Export and Import	10	✓
8	Maximizing economic income Minimizing virtual water use	Internal product, Export and Import	15	✓
9	Maximizing economic income Minimizing virtual water use	Internal product, Export and Import	20	✓
10	Maximizing economic income Minimizing virtual water use	Internal product, Export and Import	25	✓

sorting, is the basis of the most of the multi-objective evolutionary optimization algorithms. The steps to implement the NSGA-II multi--objective optimization model are as follows (Fig. (1)) (more information can be found in Deb and Zitzler, 2001):

(1) Initial Random Parents Generation (P_0) with a population of possible solutions of size of N.

(2) Sorting the first generation of parent solutions according to the non-dominated standing. The sets of produced solutions are sorted using the non-dominated ranking method. By definition, solution X_2 is dominated by X_1 if the following two conditions are satisfied.

- X_1 is not worse than X_2 in all the defined objective functions.
- X_1 is better than X_2 in at least in one of the objectives,.

(3) Considering a rank proportional to the level of each non dominated solution rank 1 is assigned to the best solutions set, rank 2 to the second best solutions set, and so on.

(4) Generating the children population (Q_0) of size N using selection, crossover, and mutation operators.

(5) Production of the new, improved, generation, including selected parents and their offspring chromosomes (i.e., solutions).

(6) Repeat step 5 until reaching a termination criterion, such as a specified number of iterations.

The number of iterations and the size N of the population of solutions are set equal to 150,000 and 100 respectively. The accuracy of the NSGA-II calculated solutions of the bi-objective model is verified by solving two single-objective optimization models, one for the minimization of virtual water use and the other for the maximization of net revenue using the software Lingo. The endpoints of the Pareto front are compared with the single-objective optimization results.

2.3. The Nash bargaining method

Solving the multi-objective optimization provides a set of non-dominated solutions, or Pareto front. Among the solutions located on the Pareto front, the most appropriate answer can be found using a conflict-resolution method (Beygi et al., 2014). Here, the Nash bargaining method is implemented, which is described briefly below.

The Nash bargaining method assigns a utility function to each player of a game. The higher the goal of a player, the higher its utility function is, and vice versa. If the utility function of player i is represented by u_i and$S = \{u_1, u_2, u_3, ., u_N\}$denotes the N-dimensional set of utility functions, each point in the set represents a solution of the conflict resolution problem. In contrast to the set points of S there is a point which is referred to as the disagreement point (d). H_d measures the degree of disagreement at the d point. The pair (S, d)represents the set position, where all members of the set $S$are larger than$d$(Ganji et al., 2007). The Nash bargaining method maximizes the following function with respect to the utilities:

$$Max.\prod_{i=1}^{F}(u_i - d_i) \tag{8}$$

where F denotes the number of objective functions. More details of the Nash bargaining method can be found in (Nash, 1950).

2.4. Optimization scenarios

This work optimizes the virtual water trade under 10 different water prices. Under Scenarios 1 through 5 the price of water is gradually increased (by five cents per scenario with scenario 1 having the lowest price) up to the price of unsubsidized domestic water in Iran. Moreover, the independence constraints (Eq. 4 and Eq. 5) are no applied to these scenarios. This means that the country is allowed to import goods to supply the nation's demand. These scenarios, therefore, represent different levels of water prices. Scenarios 6 through 10 enforce the independence and security of production constraints in addition to the gradual increase of water price. This means the country must produce at least 50% of its demand internally. Additional information about the scenarios is presented in Table 2.

3. Case study

This study investigates international virtual water trade established by strategic agricultural and industrial products. The bi-objective

Table 3
Iran's strategic agricultural and industrial product specifications.

	Specifications	Virtual water	Internal production amount	Internal sale price	Export amount	Export price	Import amount	Import price
	Unit	m^3/tons	10^3 tons	dollar/tons	10^3 tons	dollar/tons	10^3 tons	dollar/tons
Agricultural products	Wheat	3184	13,300	153	440	255	74	279
	Rice	3531	3106	1329	0	2538	1294	938
	Barley	1534	3102	147	0	750	2673	194
	Date	2685	1223	1617	256	982	0	982
	Potato	326	5143	183	551	506	1	1664
	Tomato	349	5667	287	691	509	0	509
Industrial products	Steel	28	21,884	2162	8616	395	2894	737
	Iron ore	4	39,540	121	247	420	0	97
	Aluminum	88	351	878	175	1770	153	1075
	Copper	14	160	2733	101	1953	29	6666
	Cement	74	54,720	12	12,300	33	19	1685

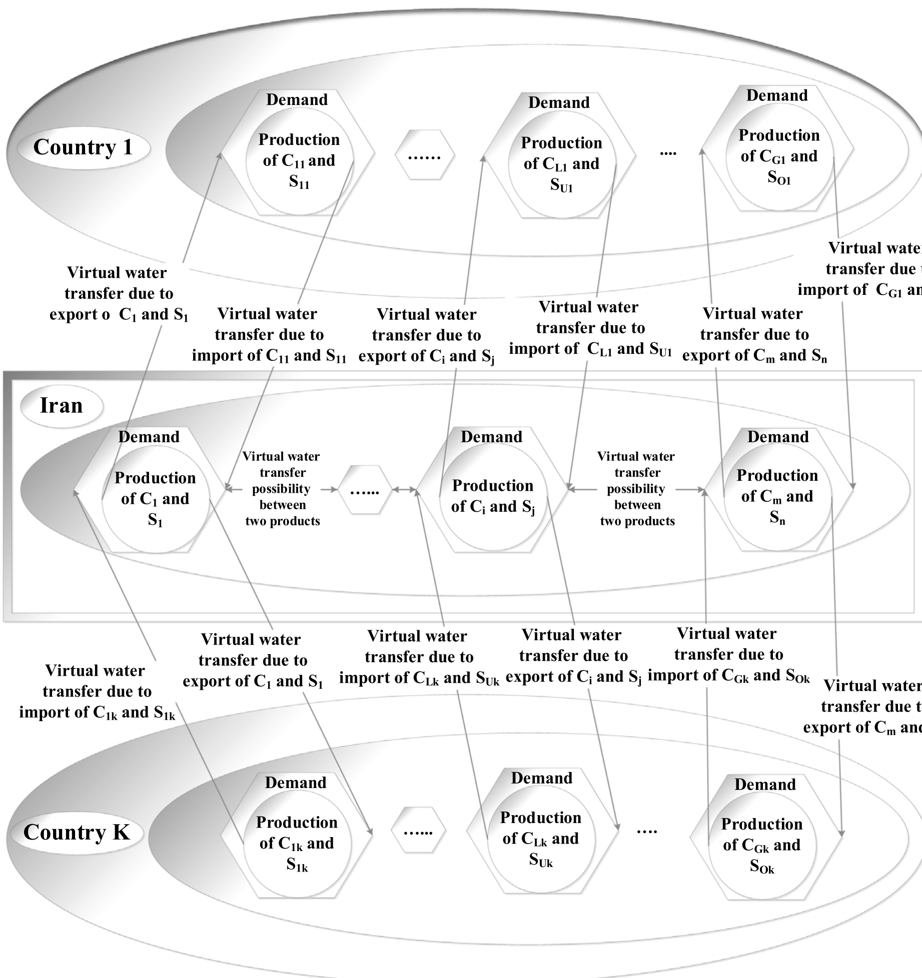

Fig. 2. Virtual water trade schematic of the agricultural and industrial sectors.

optimization model introduced above is applied to Iran. Almost 40% of Iran's lands have agricultural potential. But, due to the poor land, soil, and water management and the condition of the water distribution networks only about 10% of Iran's agricultural land have acceptable suitability for agricultural activities which accounts for about 92% of the country's water use (Mesgaran et al., 2017; Bozorg-Haddad, 2018). Six strategic agricultural products have been considered in this study: Wheat, Rice, Barley, Dates, Potatoes, and Tomatoes (see Table 3).

Iran has several active and valuable industries, such as steel, petrochemical, and cement. Obviously, these industries, despite their low total use of country's available water compared to the agricultural sector (roughly about 2% of the total water withdrawal) contribute substantially to Iran's economy. Steel, Aluminum, Copper, Iron ore, and Cement are the industrial products considered in this work (see Table 3).

All the products considered in this study are among the so-called "strategic products", which means that these products have at least one of the following features: (a) large virtual water consumption, and (b) large volumes of imports and exports. Iran's virtual water trade schematic for agricultural and industrial sectors is shown in Fig. 2. The agricultural and industrial data were provided by Iran's Ministry of Agriculture and the Ministry of Industry, Mining and Trade, respectively.

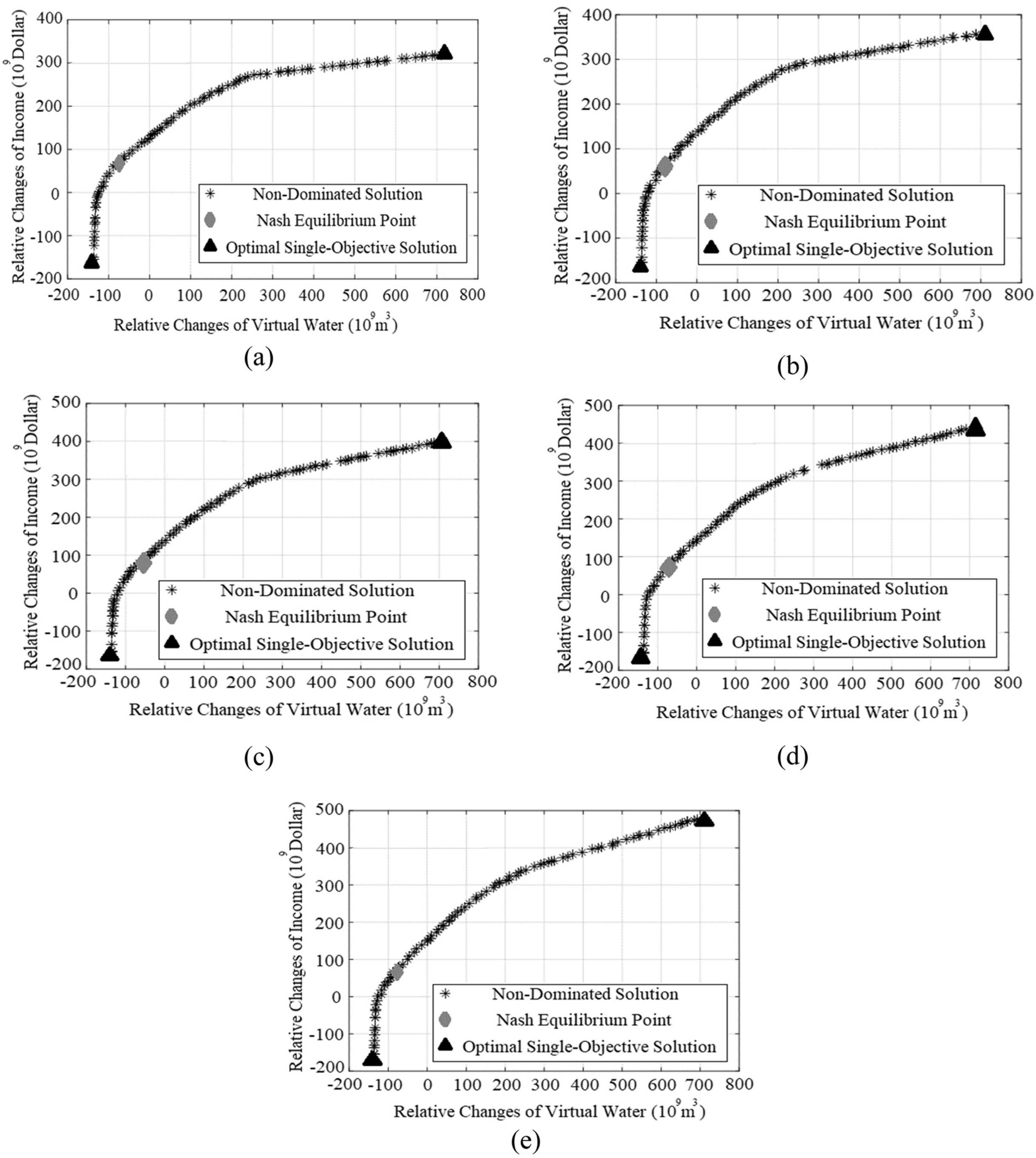

Fig. 3. The set of non-dominated solutions, Nash equilibrium point and optimal single-objective solutions for Scenarios 1–5 ((a) through (e)).

4. Results and discussion

This work identifies a set of optimal solutions that minimize the virtual water use and maximize revenue under several water pricing scenarios. It should be noted that virtual water flow of trade parameters (internal production, import and export) is calculated by multiplying the specific virtual water and trade parameters' amount.

4.1. NSGA-II and Nash equilibrium solution

Solving the optimization problem using the NSGA-II method produces Pareto fronts for Scenarios 1–5 and 6–10 (Figs. 3 and 4). It is seen in Figs. 3 and 4 the Nash equilibrium point and two global solutions for the two single-objective optimizations (minimizing virtual water use and maximizing economic income), which were calculated by Lingo. The reference points (0,0) in Figs. 3 and 4 represent Iran's virtual water consumption and economic income in 2018. Thus, the negative values on the horizontal axis represent less use of virtual water use than in 2018, and the positive numbers represent more virtual water use relative to the historical values in 2018. Similarly, the negative and positive values on the vertical axis represent less economic and more revenue, respectively, than in 2018.

A large increase in the water price causes dissatisfaction and tensions among users. Therefore, the optimal trend of virtual water trade (Pareto front) is revealed by the gradual increases in water price (Fig. 3). Under Scenarios 1 through 5 the water price increases, and the slope of the Pareto front increases also. In other words, the increase of water price leads to larger water savings with a constant revenue. It is evident in

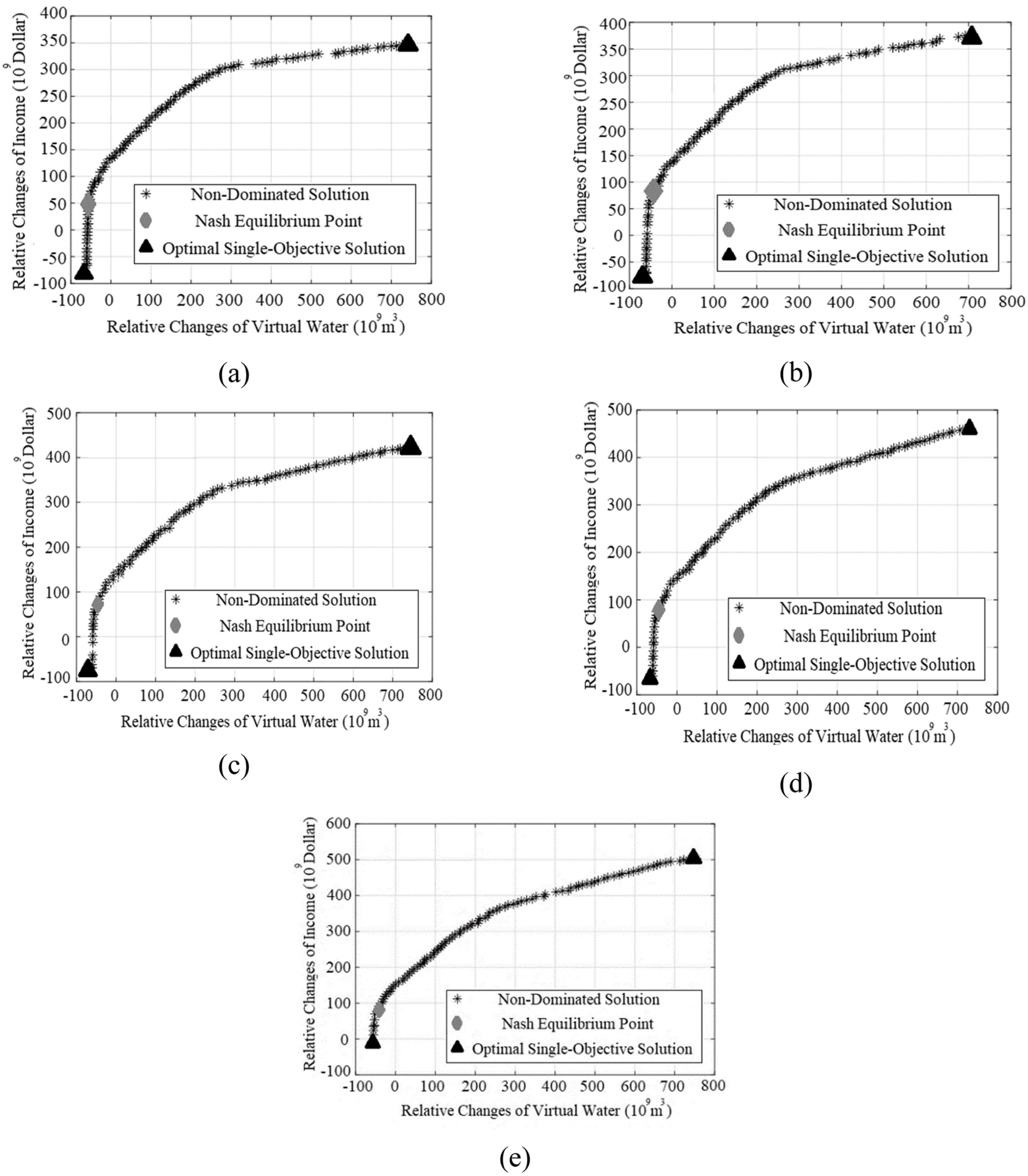

Fig. 4. The set of non-dominated solutions, Nash equilibrium point and optimal single-objective solutions for Scenarios 6–10 ((a) through (e)).

Fig. 4 that under Scenarios 6 through 10, due to the independence constraint, virtual water use (about 65 billion cubic meters) decreases compared to the first five scenarios (130 billion cubic meters). Furthermore, the increase of water price at each stage results in a rising Pareto front slope, which means the increase of water price leads to saving more water with a constant revenue.

Under Scenarios 1–5 the minimization of the virtual water use objective leads to about 1% change of the global optimal solution compared to the endpoints of the Pareto front. Similarly, for maximizing economic revenue, the global optimal point is 1% less than the endpoints of the Pareto front, which shows that the NSGA-II model optimizes the virtual water trade with high accuracy compared to the single objective problem solved by Lingo. Under Scenarios 6–10 the global solutions for single-objective optimizations differ by about 1.5% compared to the Pareto front endpoints, which demonstrates the high accuracy of the NSGA-II model in optimizing the virtual water trade. The next section discusses the Nash equilibrium solutions and the average of all the Pareto solutions.

4.2. *Virtual Water Trade optimization without independence constraint (Scenarios 1–5)*

4.2.1. *Agricultural products*

Fig. 5.a-e show the share of each agricultural products from internal production, imports, and exports. Also, the average of all Pareto solutions for the considered scenarios are listed in Table 4. It is seen that the

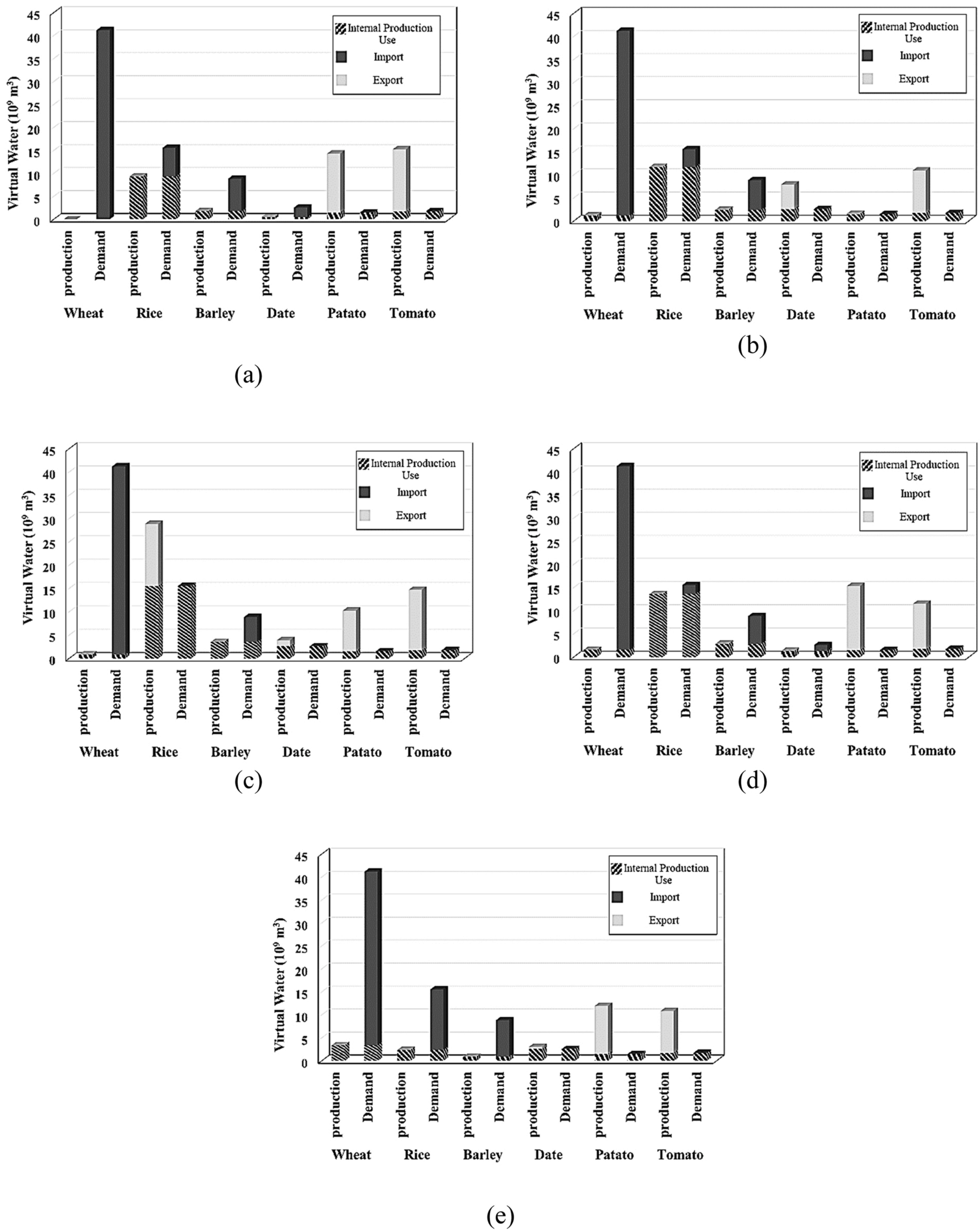

Fig. 5. Comparison chart of virtual water trading parameters (internal production, export, and import) for agricultural products of Scenarios 1–5 ((a) through (e)) at the Nash equilibrium point.

virtual water use increases (from 0.1 to 3.8 (10^9 m^3)) with increasing water price because of the higher yield of wheat production with higher water application. Yet, even with the increase of wheat production the internal production is about 5% of the total demand (for Scenario 5). More than 95% of wheat demand is supplied by importing it from other countries. Clearly, the virtual water export of this product should be equal to zero for all the scenarios. According to Table 4, the internal supply of wheat ranges between 95 and 569 (103 tons) with increasing in water price, while imports decline from 12,843 to 12,447 (103 tons). This shows that the pricing scheme reveals the significant role of internal production for meeting the country's demand.

No noticeable trend is observed for rice with changes in water price and under scenarios 1, 2, 4, and 5 the country's rice demand is supplied by internal production and imports. Four of the five scenarios call for no

Table 4
Average amount of trade for Pareto front solutions for agricultural products (10^3 tons).

		Scenario									
Product	Trade Parameter	1	2	3	4	5	6	7	8	9	10
Wheat	Import	12,635	12,843	12,633	12,631	12,447	6392	6458	6438	6150	6444
	Export	0	0	0	0	0	0	0	0	0	0
	Internal Production Use	95	240	569	357	380	6495	6494	6539	6523	6510
Rice	Import	2480	378	0	1862	4360	2157	2152	2156	1807	2075
	Export	0	0	1699	0	0	0	0	0	0	0
	Internal Production Use	1286	2151	4400	1584	1095	2250	2225	2224	2210	2215
Barley	Import	4409	3808	3838	2733	1765	1485	2873	2457	2598	2813
	Export	0	0	0	0	0	0	0	0	0	0
	Internal Production Use	1575	1716	1726	2195	2210	3960	2908	2963	2948	2949
Date	Import	541	0	0	578	0	473	469	405	452	470
	Export	0	1913	927	0	875	0	0	0	0	0
	Internal Production Use	159	722	967	432	967	495	504	512	512	517
Potato	Import	0	0	0	0	0	0	0	0	0	0
	Export	35,965	35,973	31,487	37,668	30,876	15,121	16,801	14,603	13,968	16,427
	Internal Production Use	4592	4592	4592	4592	4592	4592	4592	4592	4592	4592
Tomato	Import	0	0	0	0	0	0	0	0	0	0
	Export	30,546	32,472	37,849	34,037	25,671	13,038	19,079	31,386	34,289	35,716
	Internal Production Use	4976	4976	4976	4976	4976	4976	4976	4976	4976	4976

rice exports. Table 4, shows the rice imports vary from 378 to 4360 (103 tons), and the internal production varies from 1095 to 4400 (103 tons).

Barley has a high virtual water use and relatively low price. Therefore, the model results establish that exporting barley is not a beneficial option, and so, the virtual water use is equal to 0 in this instance. The supply of barley to meet demand would be best accomplished by imports, which implies redistributing water which has been historically used for barley toward other goods. Also, the import amount decreases from 4409 to 1756 (103 tons), while internal production varies between 1575 to 2210 (103 tons). Therefore, imports have a more significant role in meeting the domestic demand.

Scenarios 2, 3, and 5 indicate exports of dates; however, Scenarios 1 and 4 indicate that, imports of dates have a high virtual water use, and would play a major role providing the country's demand. The results listed in Table 4 establish that there are no detected trends for the trade of dates, as there is a large internal production, which varies from 159 to 967 (103 tons).

Two products, i.e., potatoes and tomatoes, are profitable crops and good options for export. Potato imports under all scenarios equal zero. The results of Table 4 indicate that the internal production, in addition to meeting the country's demand (4592 (10^3 tons)), leads to large exports (about 34,000 (10^3 tons)) because this crop is profitable in addition to having a low water use. Tomato imports equal 0 under all scenarios, and internal production, in addition to meeting the country's demand (4976 (10^3 tons)) produces large exports (which vary from 25,671 to 37,849 (10^3 tons)).

4.2.2. Industrial products

Concerning industrial production, according to Fig. 6(a) - (e), the imports of all understudied products equal to zero, and their virtual water at the Nash equilibrium point is 0. Therefore, the country meets all its demands by internal production. Also, in this group of industrial products, cement has the largest share of virtual water, and, in addition to meeting domestic demand, it has large exports of virtual water under some scenarios. Overall, the experts decline with increasing water price. The export of steel features an increasing trend with increasing water prices.

Table 5 shows the average of all the Pareto front solutions. It is seen in Table 5 that steel imports equal 0, and the country's demand (16,162 (10^3 tons)) is met by internal production. In addition, large exports are called for which vary from 21,121 to 28,702 (10^3 tons). Under all scenarios the domestic demand for aluminum is met by internal production (329 (10^3 tons)), and the exports vary from 179 to 255 (10^3 tons). Also, the steel imports are equal to 0 under all scenarios. Iron imports amount to 0. Internal iron production meets the domestic demand (37,113 (10^3 tons)) and produces a surplus for exports (about 44,000 (10^3 tons)). Copper imports equal zero under all scenarios. Copper internal production meets the domestic demand and allows exports that vary between 109 and 216 (10^3 tons). Cement has the largest share in the virtual water trade, and its production, in addition to meeting domestic demand meeting (42,439 (10^3 tons)), provides significant exports that vary between 19,057 and 30,340 (10^3 tons).

It is noticeable that optimization under the increased water price condition raises the total revenue of the agriculture and industry sectors significantly. Scenario 1–5 produce an increase in the total revenue equal to 58.47, 39.02, 73.31, 66.35 and 54.63 million dollars, respectively, compared with the revenue under actual water price condition in 2018.

4.3. Virtual water trade optimization with the independence constraint (Scenarios 6–10)

The independence constraint requires that at least 50% of country's demand of the product be supplied internally.

4.3.1. Agricultural Products

It is seen in Fig. 7(a) – (e) that the virtual water use increases with increasing production compared to the Scenarios 1–5. For wheat, the export of virtual water is equal to 0 under scenarios 6–10, and the virtual water associated with internal production increases to about 50% of the total virtual water required for wheat. The exported virtual water with rice, barley, and dates is equal to 0 for scenarios 6–10. Similar to Scenarios 1–5 potatoes and tomatoes have significant virtual water uses due to their large production, which leads to a larger amount of virtual water export.

Table 4 shows that the average internal production ranges between 6494 and 6539 (10^3 tons) to meet the internal wheat demand, which is slightly over 50% of the total demand. This production equals 50% of the when the independency constraint is enforced. However, due to the wheat's high virtual water use and low profitability, more production is not justifiable. Concerning rice, the export is equal to 0 under scenarios 6–10. Rice imports vary between 1807 and 2157 (10^3 tons), and the domestic production ranges between 2210 and 2250 (10^3 tons). More than 50% of the barley demand is supplied domestically, i.e., 2908 to 3960 (10^3 tons), while the barley import varies between 1485 and 2873 (10^3 tons). The barley exports equal to 0 under scenarios 6–10.

All of the country's potato demand is supplied domestically, 4592 (10^3 tons), and the rest of production is exported. Analogous to the first

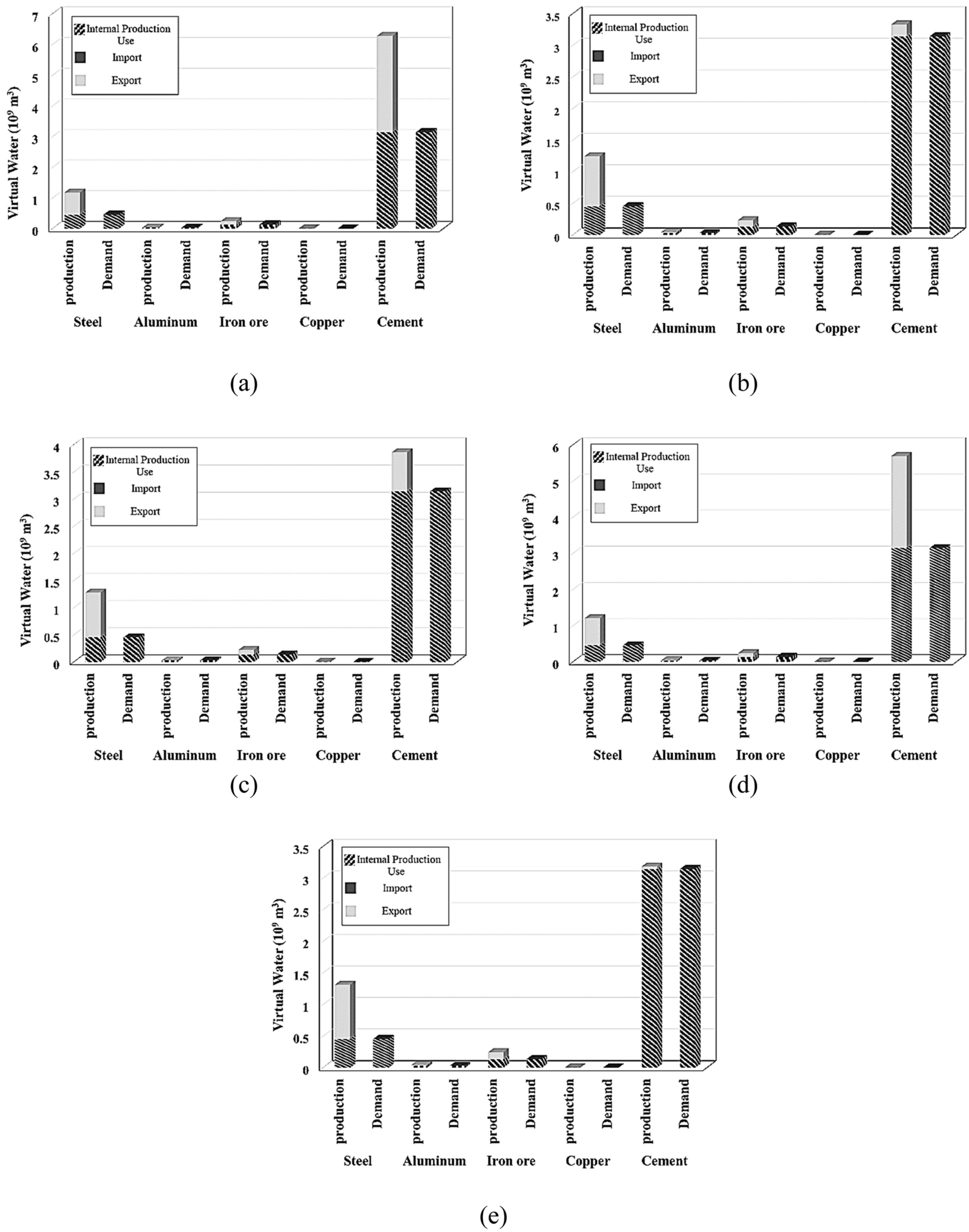

Fig. 6. Comparison chart of virtual water trading parameters (internal production, export, and import) for industrial products of Scenarios 1–5 ((a) through (e)) at the Nash equilibrium point.

Table 5
Average amount of trade for Pareto front solutions for industrial products (10^3 tons).

Product	Trade parameter	Scenario									
		1	2	3	4	5	6	7	8	9	10
Steel	Import	0	0	0	0	0	0	0	0	0	0
	Export	21,121	28,702	27,863	28,344	26,685	16,574	18,096	21,711	15,887	24,935
	Internal Production Use	16,162	16,162	16,162	16,162	16,162	16,162	16,162	16,162	16,162	16,162
Aluminum	Import	0	0	0	0	0	0	0	0	0	0
	Export	197	248	179	229	255	93	18	32	132	239
	Internal Production Use	329	329	329	329	329	329	329	329	329	329
Iron ore	Import	0	0	0	0	0	0	0	0	0	0
	Export	46,870	44,432	42,671	42,313	46,675	48,550	45,725	47,218	48,034	47,402
	Internal Production Use	37,113	37,113	37,113	37,113	37,113	37,113	37,113	37,113	37,113	37,113
Copper	Import	0	0	0	0	0	0	0	0	0	0
	Export	109	216	195	155	126	178	56	58	164	312
	Internal Production Use	87	87	87	87	87	87	87	87	87	87
Cement	Import	0	0	0	0	0	0	0	0	0	0
	Export	22,559	30,340	20,463	28,364	19,057	2116	3806	3228	3958	12,100
	Internal Production Use	42,439	42,439	42,439	42,439	42,439	42,439	42,439	42,439	42,439	42,439

five scenarios higher exports of potatoes, 13,968–16,801 (10^3 tons), preclude any imports of this crop. Similar strategy is obtained for tomatoes, whose exports vary between 13,038 and 35,716 (10^3 tons), and there are no imports. Therefore, it is clear that the country's tomato demand can be fully supplied by Iran's farmers. Between 45% and 49% of the domestic demands for rice, barley, and dates are met by imports. This means that the optimal solutions call for internal production of at least 50% of the domestic demand, and importing the rest of the demand for these goods is much more profitable.

4.3.2. Industrial products

Fig. 8(a) – (e) establish that virtual water imports for all industrial products obtained with the Nash equilibrium point are equal to zero. It means that the domestic demands for these products is met by internal production. Also, increasing the water price leads to increases in the virtual water exports of steel and cement. This means that by increasing the price of water the production of industrial goods increases to compensate for the reduction in agricultural trade income.

The results in Table 5 establish that the steel imports equal zero, and the country's demand (16,162 (10^3 tons)) is fully met by internal production. Moreover, the steel exports are relatively high, 15,887–24,935 (10^3 tons). The domestic demand for aluminum under scenarios 6–10 is supplied by internal production (329 (10^3 tons)), and its exports vary between 18 and 239 (10^3 tons). Also, the aluminum, iron, and copper imports equal zero under scenarios 6–10. The internal production of iron ore supplies the domestic demand (37,113 (10^3 tons)), and, in addition, it allows for iron ore exports (about 47,000 (10^3 tons)). The internal production of copper provides excellent opportunity for exports. In addition to supplying the domestic demand copper exports range from 56 to 312 (10^3 tons). Cement has the largest share of the virtual water trade and total production. Domestic cement demand is about 42,439 (10^3 tons), which can be supplied within the country. Moreover, the export of cement is estimated at about 2116 to 12,100 (10^3 tons) under scenarios 6–10. Table 5 shows that by increasing the price of water the total export of industrial products increases. By increasing the water price water is transferred from the agricultural to the industrial sector to increase revenue based on their water use.

The management of the virtual water trade under the increased water price condition raises the total revenue of the agricultural and industrial sectors significantly. Scenarios 6–10 produce increases in revenue equal to 49.17, 76.13, 70.12, 81.55 and 82.82 million dollars, respectively, compared with the revenue under the actual water price condition in 2018.

5. Concluding remarks

Various studies have monitored the amount of virtual water trade by countries. In this study, on the other hand, the virtual water trade of Iran's strategic agricultural and industrial products has been investigated for year 2018, and the optimal trade portfolio is established by means of the multi-objective optimization NSGA-II algorithm considering a range of water prices. The two objectives of the optimization model are to maximize revenue and to minimize virtual water use. Water price is raised from 0 to 25 cents per cubic meter, which is the current water price in Iran. Also, production security is added to the optimization model as a constraint, whereby at least 50% of the country's demand must be supplied domestically.

The results showed that among the strategic agricultural products wheat has the highest share of virtual water use, about 40 (10^9 m^3). The production of agricultural and industrial commodities increases when the production security constraint is applied. Also, it was found that on average wheat, rice, barley, and dates imports accounted for about 45–49% of their total demands. The potato and tomato exports have a significant role in total domestic production, 76% and 80%, respectively. Our results reveal that the industrial demand can be met by internal production, and industrial imports equal zero. By raising the water price, the industrial production would increase to compensate for the reduction in agricultural revenue, which means that as the water price increases its use is transferred to more profitable production, in this case to industrial commodities.

We acknowledge the complexity of planning and managing the domestic production and international trade, and for this reason this study begins to shed light on the virtual water trade involving agricultural and industrial products. Thus, neglecting further constraints and policies was herein inevitable. Future research will address the complexities of managing domestic production and trade, which would broaden this study to include the impact of climate change, considering risk and the uncertainty analysis of trade, and the development of a modern trade portfolio in future studies.

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CRediT authorship contribution statement

Mohammad Delpasand: Software, Formal analysis, Writing – original draft. **Omid Bozorg-Haddad**: Conceptualization, Supervision, Project administration. **Erfan Goharian**: Validation, Writing – review

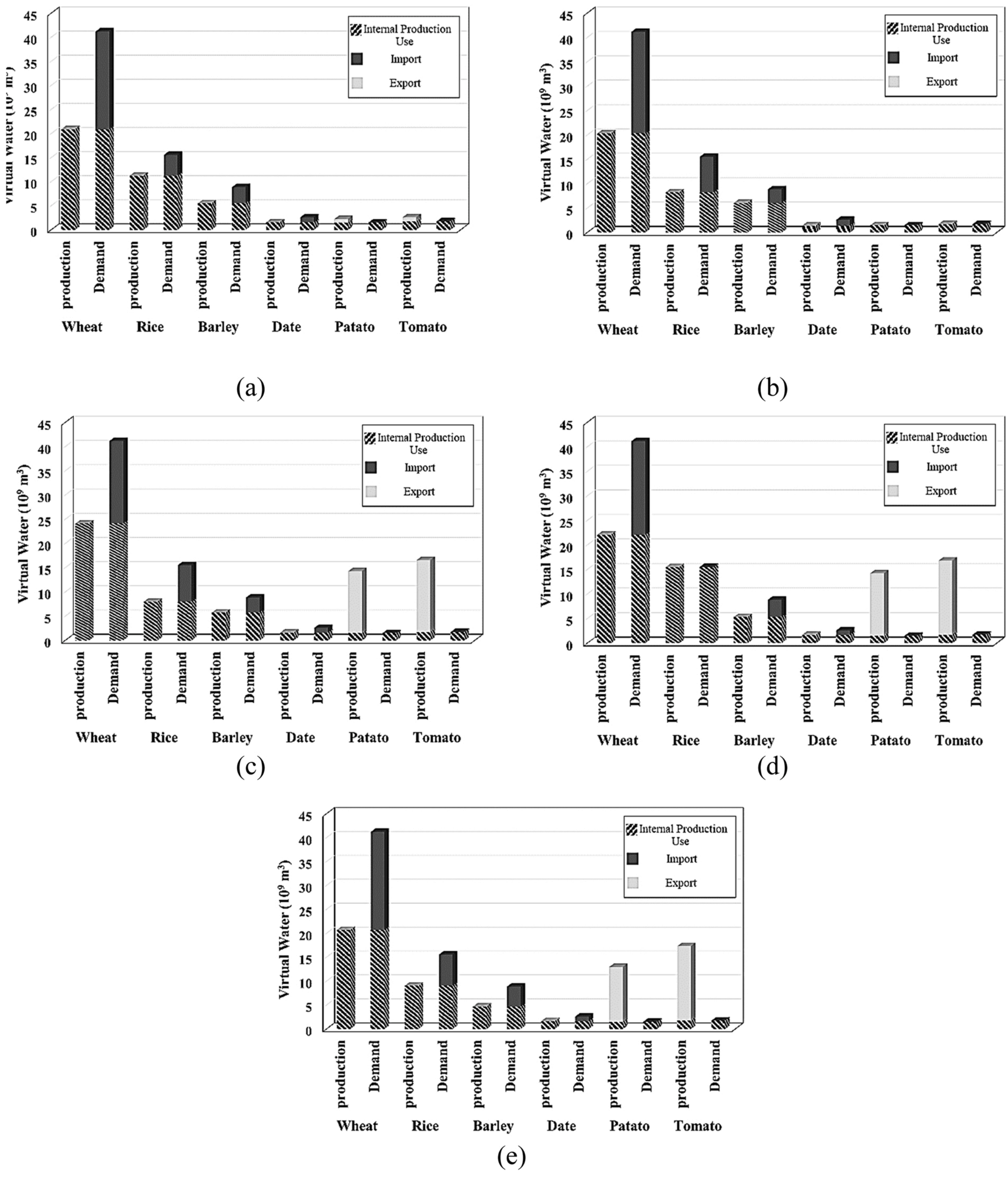

Fig. 7. Comparison chart of virtual water trading parameters (internal production, export, and import) for agricultural products of Scenarios 6–10 ((a) through (e)) at the Nash equilibrium point.

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Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

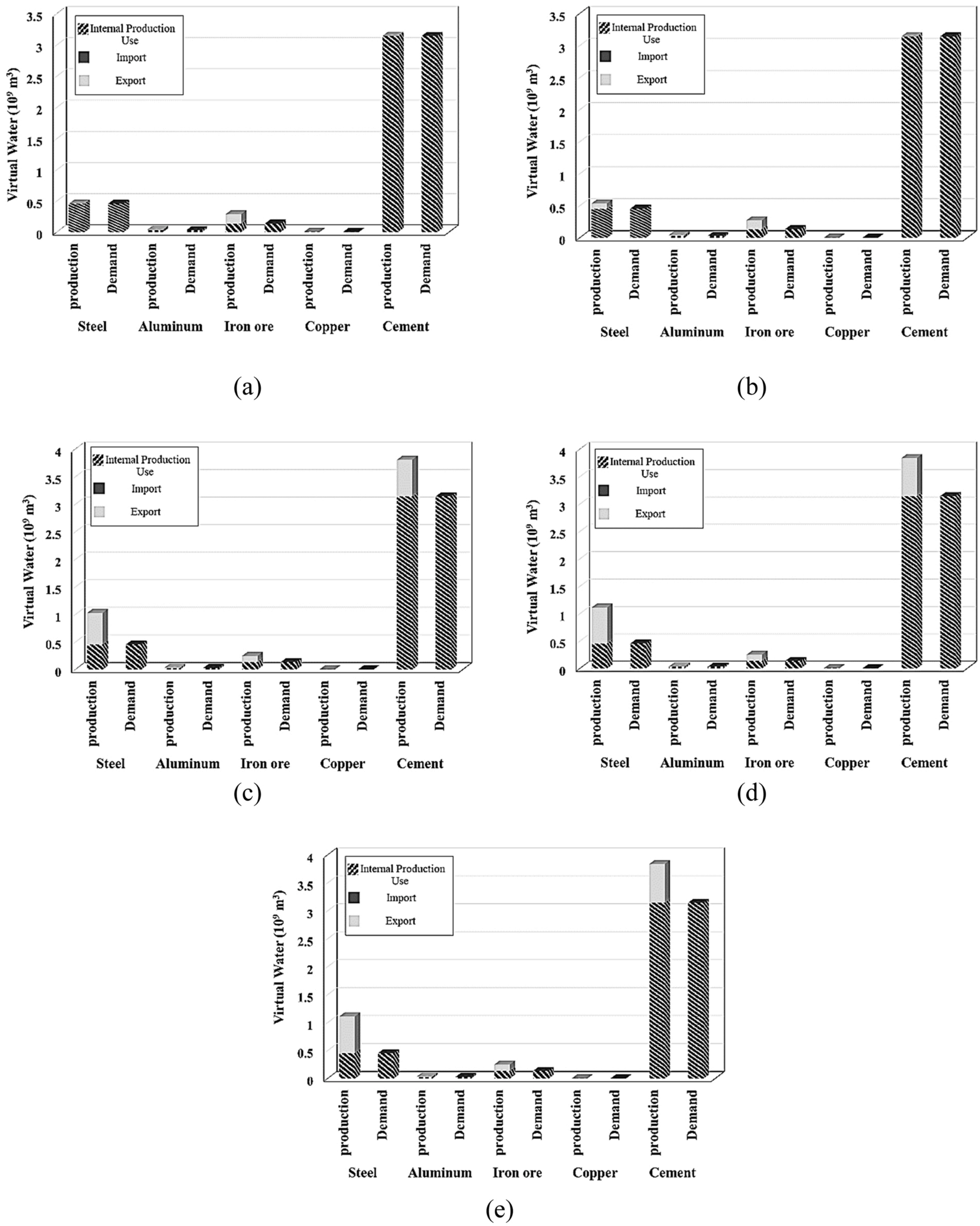

Fig. 8. Comparison chart of virtual water trading parameters (internal production, export, and import) for industrial products of Scenarios 6–10 ((a) through (e)) at the Nash equilibrium point.

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Ethics Approval

All authors accept all ethical approvals.

Consent to Participate

All authors consent to participate.

Availability of data and materials

The data that support the findings of this study are available from the corresponding author upon reasonable request.

Code availability

The codes that support the findings of this study are available from the corresponding author upon reasonable request.

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