Virtual Water Trade and Its Implications on Water Use Efficiency and Sustainability in Pakistan

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Abstract
This study analyzes inter-provincial and international virtual water trade of selected crops and examines its implications for water-use efficiency and sustainability in Pakistan. Using data for 2020–21, the direction and magnitude of virtual water flows were assessed for major crops, fruits, and vegetables across provinces. The results show that Khyber Pakhtunkhwa (KPK) was a major net importer of virtual water (9,168 Mm^3), followed by Sindh (2,616 Mm^3) and Balochistan (1,090 Mm^3), reflecting substantial regional imbalances in water use and crop production. Rice emerged as the leading exporter of virtual water, while cotton lint and wheat dominated virtual water imports. Comparisons with global benchmarks reveal that Pakistan exhibits lower crop yields and higher water use per unit output for most crops, indicating inefficient water utilization, except in cotton lint production. Monetary returns per cubic meter of water were highest for cotton lint, followed by vegetables and fruits, highlighting the potential for reallocating water toward higher-value crops. The findings underscore the need for policy-driven crop specialization based on provincial comparative advantage and water availability. Integrating virtual water trade considerations into agricultural and water resource policies can improve water-use efficiency, reduce pressure on scarce water resources, and enhance the sustainability and climate resilience of Pakistan’s agricultural sector.
Keywords: Virtual water trade, Water use efficiency, Sustainability, Major crops, Fruits and vegetables

1. Introduction

Water is a vital input for agricultural production and plays a critical role in ensuring global food security. Agriculture accounts for nearly 70 percent of global freshwater withdrawals being the largest water consuming sector (FAO, 2011). Rapid population growth, urbanization, and climate change have intensified pressure on already limited freshwater resources, particularly in arid and semi-arid regions. Improving water-use efficiency in agriculture has therefore become a central policy concern, especially in developing countries where inefficient irrigation practices and water-intensive cropping patterns prevail (Mekonnen & Hoekstra, 2011; Goswami & Nishad 2018; Fallenmark 2013; and Grey et al. 2013). Kummu et al., 2016 argued that even water-rich nations are struggling to cope with growing freshwater scarcity to fulfill the minimum demand.

Pakistan's economy is heavily dependent on agriculture, which remains the largest user of freshwater resources in the country. Pakistan's limited water resources are under immense stress due to the rising population, sedimentation in reservoirs, dwindling river supplies, and climate change. However, Pakistan is increasingly facing severe water stress, with per capita water availability declining from over 5,000 cubic meters in 1951 to less than 1,000 cubic meters in recent years, approaching the threshold of water scarcity (PCRWR, 2022 and GOP, 2022). Over 90 percent of agricultural production relies on irrigation, primarily supported by the Indus Basin Irrigation System, one of the largest contiguous irrigation networks in the world (World Bank, 2019). Indus River and its tributaries irrigate 48 million acres of land having an average annual withdrawal of 101 MAF of water. It is estimated that approximately 50 MAF groundwater is pumped through 1.2 million tube wells (Qureshi, 2011).

In this context, the concept of virtual water has emerged as an important analytical framework for understanding the hidden flows of water embedded in agricultural commodities. The term "virtual water," first introduced by Allan (1998), refers to the volume of water consumed during the production of goods and services, particularly agricultural crops, which is implicitly traded when these commodities are exchanged across regions or countries. Virtual water trade allows water-scarce regions to conserve domestic water resources by importing water-intensive products, while water-abundant regions can specialize in their production, thereby improving overall water-use efficiency (Hoekstra & Hung, 2002; Hoekstra et al., 2011). Uneven temporal and spatial distribution of water resources has contributed to water crises in many countries and virtual water trade constitutes a means of dealing with such crises (Delpasand et al., 2023).

In recent years, virtual water trade has garnered significant attention and has become an important means for balancing the water budget. Virtual water trade can also have adverse effects on the exporting country's water balance and the economy. In Pakistan, changing climate over-extraction, unsustainable consumption, have put additional pressure on maintaining water sustainability. The water crisis is putting the largest sector of the country's economy at risk. In this context, all major crops (Rice, Wheat, Cotton, Sugarcane, and Maize), fruits, and vegetables mainly contribute to domestic export among provinces. These crops consume a hefty amount of water. The exporting region/country's water balance and the economy may also get adversely affected by virtual water export. Al-Badri et al., 2023 argues that any agricultural policy will not attain success if water policy does not have a presence based on economic and environmental foundations.

A growing body of international literature highlights the importance of virtual water trade as a mechanism for mitigating water scarcity and promoting sustainable resource allocation. Hoekstra and Hung (2002) provided the first quantitative assessment of virtual water flows by estimating the water embedded in internationally traded agricultural commodities, demonstrating that virtual water trade allows water-scarce regions to conserve domestic water resources by importing water-intensive crops, thereby improving overall water-use efficiency. Subsequent global assessments have shown that nearly 20 percent of the water used in global food production is traded virtually rather than consumed domestically, underscoring the scale and significance of virtual water exchanges (Mekonnen et al., 2024). Empirical evidence further suggests that virtual water trade patterns do not necessarily align with hydrological endowments; for instance, Jiang et al. (2015) found that several water-scarce agricultural provinces in China were net exporters of virtual water, while economically advanced but production-limited regions such as Beijing and Tianjin relied heavily on imports. Similar findings from the Middle East, China, and South Asia indicate that trade-based redistribution of water-intensive crops can reduce pressure on local water resources and enhance food security when aligned with regional comparative advantages (Yang et al., 2006; Chapagain & Hoekstra, 2008; Liu et al., 2017). However, Carr et al. (2012) highlighted that virtual water trade networks are subject to substantial temporal variability driven by changes in production, trade patterns, and climatic conditions, which can increase vulnerability to external shocks. Despite these insights, limited attention has been given to comprehensive, policy-oriented analyses that integrate inter-regional virtual water flows, water-use efficiency, and sustainability considerations particularly in water-stressed countries like Pakistan highlighting a clear gap in the existing literature.

In Pakistan, empirical research on virtual water trade remains limited despite increasing water stress and heavy reliance on irrigated agriculture. Existing studies have primarily focused on national-level water footprints or individual crops, offering useful insights into aggregate virtual water flows but providing limited understanding of inter-provincial dynamics and regional water-use efficiency (Ashfaq et al., 2019; Ahmad et al., 2021).

These studies indicate that Pakistan continues to export water-intensive crops such as rice and sugarcane, even from water-stressed regions, contributing to groundwater depletion and unsustainable water use. However, the existing literature largely overlooks provincial disparities in virtual water trade, comparisons with global water-use efficiency benchmarks, and the economic returns per unit of water consumed. Moreover, limited attention has been paid to the policy implications of virtual water trade for crop specialization, climate resilience, and sustainable water governance. This lack of comprehensive, policy-oriented analysis underscores the need for an integrated assessment of inter-provincial and international virtual water trade and its implications for water-use efficiency and sustainability in Pakistan.

Therefore, this study analyzes inter-provincial and international virtual water trade of selected crops, fruits, and vegetables in Pakistan for the year 2020–21, with a focus on its implications for water-use efficiency and sustainability. The study examines the direction and magnitude of virtual water flows across provinces and borders, compares Pakistan's water use in agricultural production with world average benchmarks, and assesses the economic contribution of water use across major commodities. Using secondary data on area, production, consumption, and crop-specific water requirements, the research highlights patterns of virtual water exports and imports and identifies inefficiencies in water use within Pakistan's agricultural sector. The findings provide policy-relevant insights for improving crop specialization, aligning trade flows with regional water endowments, and promoting sustainable agricultural development under increasing water scarcity, over-extraction, and climate change pressures. Given the limited recent empirical evidence on virtual water trade and its implications for sustainable water resource management in Pakistan, this study addresses an important gap in the existing literature.

Material and Methods

This study utilized secondary data for its analysis. Water demand for crops i.e. rice, wheat, cotton, maize, sugarcane, fruits, and vegetables were analyzed in year 2020-21. Virtual water trade among different provinces of Pakistan was analyzed. Area under selected crops, production, per capita consumption, export, import, and water requirement data were collected from secondary sources. The total water required for the production of crops is measured by multiplying the total production of the crop by the water footprint (Nishad and Kumar, 2022). Virtual water analysis is considered a valuable method for tracking water displacement across regional boundaries. (Jeswani and Azapagic, 2011). The data on water consumed for the production of selected crops was used from the published work of Ali *et al.* (2019). The secondary data from the Pakistan Bureau of Statistics (PBS) and

Agricultural Information Management System (AIMS), Punjab were used. Water consumed for the production of the crop was calculated as;

$$W_P(i,t,p) = F_P(i,t)W_F(i) \dots \dots \dots \dots \dots \dots . . 1$$

Here $F_P(i,t)$ represents the production of the crop i in the year t in each province p. $W_F(i)$ represents the water footprint of the crop "i" used to produce a crop given as m^3 /ton. In terms of water content available in the end products of the total production of major crops.

The virtual water used in each province can be calculated by multiplying the volume of the crop consumption by multiplying the per capita consumption of each commodity with the population of the province. The virtual water consumption was calculated as;

$$W_C(i,t,p) = F_{CP}(i,t) * P_P(i) \dots \dots \dots \dots \dots \dots . . 2$$

Here $W_C(t)$ represents the virtual water consumed in the year t at each province p. $F_{CP}(i,t)$ represents the per capita consumption of the crop i in the year t at each province p. $P_P(i)$ represents the population of each province. Net water availability at each province level was calculated by subtracting water used for consumption against each commodity for the entire province population from the water consumed for the production of each crop at each province as;

$$W_N(i,t,p) = W_P(i,t,p) * W_C(i,t,p) \dots \dots \dots \dots \dots 3$$

The analysis was carried out considering the blue and green water use. 'The blue water includes the surface and groundwater, while the green water is the rainwater stored in the soil as soil moisture (Ali *et al.,* 2019).

2. Results and Discussions

The present research results provide the magnitude and direction of virtual water trade for the judicious use of this precious resource in Pakistan. The research findings are crucial for formulating national policies aimed at promoting optimal water use, thereby enhancing sustainable agricultural productivity in the country.

Province-wise virtual water trade for rice production in Pakistan

Province-wise area, production, consumption, water requirement, and water use in rice production in Pakistan are given in Table 1. The results revealed that per capita consumption was highest in Sindh followed by Khyber Pakhtunkhwa (KP), Punjab and Balochistan 22.4, 10.20, 9.6 and 9.4 kg/annum, respectively. In Pakistan overall per capita rice consumption was 12.7 Kg/year. Khyber Pakhtunkhwa imported 600 million cubic meters (Mm^3) of virtual water for rice consumption from other provinces during the study period.

Table 1. Province-wise net virtual water trade for rice production in Pakistan

Region	Area (000 acres)	Total Production (000 Tons)		Per Capita Consumption (kg/Year)	Total Consumption (000 tons)	Water Requirement (m^3/Ton	Water Use in Production (Million m^3)	Net virtual Water Trade Million (m^3)

Punjab	5917.0	5301.4		9.6	1055.9	2947.0	15623.2	12511.5
Sindh	1752.0	2416.1		22.4	1073.9	2947.0	7120.2	3955.5
KP	160.4	158.5		10.2	362.1	2947.0	467.2	-600.0
Baluchistan	413.2	543.7		9.4	115.5	2947.0	1602.2	1261.9
Pakistan	8242.6	8419.7		12.7	2616.3	2947.0	24812.8	
	Source: Authors' calculations Data: (PBS 2019 and AMIS Punjab 2021)							

Province-wise virtual water trade for wheat production in Pakistan

Province-wise area, production, consumption water requirement, and water use in wheat production in Pakistan are given in Table 2. The result revealed that per capita consumption was highest in Balochistan followed by KP, Punjab, and Sindh. In wheat consumption, Khyber Pakhtunkhwa and Balochistan provinces imported around 3652 and 27 Mm^3 virtual water from other provinces in said period.

Table 2. Province-wise net virtual water trade for wheat production in Pakistan

Region	Area (000 acres)	Total Production (000 Tons)	Per Capita Consumption (kg/Year)	Total Consumption (000 tons)	Water Requirement (m^3/Ton	Water Use in Production (Million m^3)	Net virtual Water Trade Million (m^3)
Punjab	16670.0	20900.0	84.5	9291.9	1862	38915.8	21614.2
Sindh	2971.4	4043.2	73.0	3491.5	1862	7528.4	1027.3
KP	1882.4	1361.6	93.6	3323.0	1862	2535.3	-3652.1
Baluchistan	1131.8	1159.3	95.2	1173.8	1862	2158.7	-27.0
Pakistan	22655.7	27464.1	84.0	17277.2	1862	51138.1	
Source: Authors' calculations, Data: (PBS 2019 and AMIS Punjab 2021)							

Province-wise virtual water trade for sugar production in Pakistan

Province-wise area, production, consumption water requirement, and water use in sugar production in Pakistan are given in Table 3. The results revealed that per capita consumption was highest in Balochistan to the tune of 21.7 Kg/ annum followed by KP 19.9 Sindh 16.0 and Punjab 14.5 Kg/ annum. The Balochistan province was a net importer of around 761.9 Mm^3 water for sugar consumption. The Khyber Pakhtunkhwa province was a net importer of 412.5 Mm^3 water from other provinces and the international market.

Table 3.

Province-wise net virtual water trade for sugarcane production in Pakistan

Region	Area (000 acres)	Total Production (000 Tons)	Per Capita Consumption (kg/Year)	Total Consumption (000 tons)	Water Requirement (m^3/Ton	Water use in Production (Million m^3)	Net virtual Water Trade (Million m^3)

Punjab	1920.0	4837.6	14.5	1597.1	2887	13966.1	9355.4
Sindh	691.2	1653.5	16.0	763.8	2887	4773.6	2568.7
KP	265.5	564.3	19.9	707.2	2887	1629.2	-412.5
Baluchistan	2.3	4.0	21.7	267.9	2887	11.5	-761.9
Pakistan	2878.9	7006.5	16.2	3332.0	2887	20227.7	
Source: Authors' calculations, Data: (PBS 2019; and AMIS Punjab, 2020-21)							

Table 4.
Province-wise net virtual water trade for cotton production in Pakistan

Region	Area (000 acre)	Total Production (000 Tons)	Per Capita Consumption (kg/Year)	Total Consumption (000 tons)	Water Require-ment (m^3/Ton	Water use in Production (Million m^3)	Net virtual Water Trade (Million m^3)
Punjab	3821.0	15147.2	13.8	1520.8	6974	105636.2	95030.0
Sindh	1173.3	5591.0	13.8	661.7	6974	38991.4	34376.8
KP	0.3	1.0	13.8	490.9	6974	6.9	-3416.5
Baluchistan	142.6	473.9	13.8	170.6	6974	3304.8	2115.3
Pakistan	5137.2	21212.9	13.8	2843.9	6974	147939.1	
Source: Authors' calculations Data: (PBS 2019 and AMIS Punjab, 2020-21)							

Province-wise virtual water trade for maize production in Pakistan

Province-wise area, production, consumption water requirement, and water use in maize production in Pakistan are given in Table 5. The results revealed that per capita consumption was highest in Sindh to the tune of 17.3 Kg/ annum followed by Balochistan at 16.0 Punjab at 15.1 and KP at 13.4 Kg/ annum. Sindh and Balochistan provinces imported nearly 1807.6 and 423.0 Mm^3 water from other provinces for maize consumption, respectively.

Table 5.
Province-wise net virtual water trade for maize production in Pakistan

Region	Area (000 acre)	Total Production (000 Tons)	Per Capita Consumption (kg/Year)	Total Consumption (000 tons)	Water Requirement (m^3/Ton	Water Use in Production (Million m^3)	Net virtual Water Trade Million (m^3)
Punjab	2344.0	8039.9	15.1	1662.4	2198	17671.7	14017.8
Sindh	10.3	4.2	17.3	826.6	2198	9.3	-1807.6
KP	1138.3	891.0	13.4	475.3	2198	1958.5	913.8
Baluchistan	10.9	4.7	16.0	197.1	2198	10.2	-423.0
Pakistan	3503.5	8939.8	15.6	3197.5	2198	19649.7	
Source: Authors' calculations Data: (PBS 2019 and AMIS Punjab 2021)							

Province-wise virtual water trade for production of fruits in Pakistan

Province-wise area, production, consumption water requirement, and use in fruit production in Pakistan are given in Table 6. The results revealed that per capita consumption was highest in Punjab, to the tune of 21.9 kg/

annum followed by Sindh 19.3, KP 18.7, and Balochistan 11.4 kg/ annum. Sindh and Khyber Pakhtunkhwa were net importers of nearly 36.9 and 354.1 Mm^3 of water from other provinces with ~~some~~ a little share ~~of~~ from the international market for fruit consumption.

Table 6.
Province-wise net virtual water trade for fruit production in Pakistan

Region	Area (000 acres)	Total Production (000 Tons)	Per Capita Consumption (kg/Year)	Total Consumption (000 tons)	Water Requirement (m^3/Ton	Water Use in Production (Million m^3)	Net virtual Water Trade Million (m^3)
Punjab	295.1	4745.7	21.9	2411.4	1098	5210.7	2563.0
Sindh	156.5	888.7	19.3	922.3	1098	975.8	-36.9
KP	41.1	342.5	18.7	665.1	1098	376.1	-354.1
Baluchistan	186.3	1336.3	11.4	140.0	1098	1467.3	1313.6
Pakistan	679.0	7313.2	20.1	4133.5	1098	8029.9	

Source: Authors' calculations, Data: (PBS 2019 and AMIS Punjab 2021)

Province-wise virtual water trade for vegetable production in Pakistan

Province-wise area, production, consumption water requirement, and use in vegetable production in Pakistan are given in Table 7. The results revealed that per capita consumption was the highest in Punjab, to the tune of 61.08 Kg/ annum followed by KP and Balochistan 56.88 and Sindh 40.25 kg/ annum. Sindh and Khyber Pakhtunkhwa provinces imported nearly 775.7 and 733.0 Mm^3 of water from other provinces and international markets for vegetable consumption during the said period.

Table 7.
Province-wise net virtual water trade for fruit production in Pakistan

Region	Area (000 acre)	Total Production (000 Tons)	Per Capita Consumption (kg/Year)	Total Consumption (000 tons)	Water Requirement (m^3/Ton	Water Use in Production (Million m^3)	Net Virtual Water Trade (Million m^3)
Punjab	368.6	8001.0	61.08	6718.2	491	3928.4	629.8
Sindh	52.2	346.3	40.25	1926.1	491	170.0	-775.7
KP	49.8	526.4	56.88	2019.4	491	258.5	-733.0
Baluchistan	50.0	748.5	56.88	701.6	491	367.5	23.0
Pakistan	520.5	9622.1	59.40	12217.5	491	4724.5	

Source: Authors' calculations, Data: (PBS 2019 and AMIS Punjab 2021)

Table 8 describes the yield and water use comparison of Pakistan with the world average. The world average yields of all selected crops were higher in comparison of the country, ranging from 17 percent for wheat to 77 percent in case of maize crop. The cotton lint yield was he same. The world average use of water in producing all selected crops was less in comparison to Pakistan except in cotton lint production. The percentage of blue water use in Pakistan was significantly higher for all selected crops except cotton lint.

Table 8. Yield and Water Use Comparison with World Average

Commodity	Yield Comparison (World average-Pakistan) (%)	Water Use Comparison (World average-Pakistan) (m^3/ton)	Water Use Comparison (World average-Pakistan) (%)	Pakistan Blue water use (%)	World Blue water use (%)
Rice	29	-1460	-50	80	23
Wheat	17	-243	-13	86	21
Sugar unrefined	35	-1325	-46	80	29
Cotton lint	0	1144	16	40	36
Maize	77	-1170	-53	48	8
Fruits	25	-224	-20	45	17
Vegetables	31	-254	-52	76	18

Source: Authors calculations based on published work of Ali et al. (2019) and Mekonnen & Hoekstra (2011).

Table 9 presents the water use contribution in creating monetary value. The contribution in monetary terms of per unit (cubic meter) water use was high in the case of cotton lint production followed by vegetables and fruits. Considering international prices in calculating per unit water contribution, results varied, with vegetable production leading followed by cotton lint and fruits production.

Table 9. Monetary Value of Water Use

Commodity	Value (PKR/ton)	Value(USD/ton)	PKR /m^3 water use	USD /m^3 water use
Rice	103135	840.1	35.01	0.29
Wheat	53175	399.6	28.54	0.21
Sugar unrefined	97625	610.1	33.83	0.21
Cotton lint	2580775	2850	370.06	0.41
Maize	39775	287.6	18.10	0.13
Fruits	52500	328.1	47.81	0.30
Vegetables	39350	245.28	80.14	0.50

Source: Authors calculations based on data from Government Sources, Ali et al. (2019) and Mekonnen & Hoekstra (2011).

Table 10 shows the export and import of virtual water. Rice was the main crop in the export of virtual water followed by fruits and vegetables. Virtual water export was not observed in wheat, sugar and maize for the year 2020-21. In the year 2020-21, cotton lint was the main commodity in virtual water import followed by wheat. A nominal quantity of virtual water import was also calculated for sugar, vegetables and fruits.

Table 10. Pakistan's virtual water trade with the world

Commodity	Export (000 tons)	Import (000 tons)	Virtual Water Export (million m^3)	Virtual Water Import (million m^3)
Rice	3691.437	0	10874.97	0.00
Wheat	0	3612.638	0.00	5848.86
Sugar unrefined	0	281.329	0.00	439.44

Cotton lint	0.594	857.373	4.14	6960.15
Maize	0	0	0.00	0.00
Fruits	982.3	364.5	1078.57	318.57
Vegetables	950.4	1463.2	466.65	346.78
Source: Authors' calculations based on data from Government Sources, 2020-21, Ali et al. (2019) and Mekonnen & Hoekstra (2011).				

3. Conclusion

This study provides a comprehensive assessment of inter-provincial and international virtual water trade associated with major crops, fruits, and vegetables in Pakistan for the year 2020–21. The results reveal substantial spatial heterogeneity in virtual water flows across provinces, reflecting differences in production capacity, consumption patterns, and water endowments. The Punjab province was found to be net exporter of virtual water for all selected crops. The Khyber Pakhtunkhwa province was found to be a net importer of virtual water in rice, wheat, sugar, cotton, fruits, and vegetables. Wheat and cotton were the major commodities in the virtual water import of KP. Similarly, Sindh province was a net importer of virtual water for maize, fruits, and vegetables from other provinces. Balochistan province was a net importer of virtual water for wheat sugar and maize. These patterns indicate that virtual water trade within Pakistan plays a significant role in balancing regional food demand but does not consistently align with provincial water scarcity levels. The comparison with global benchmarks highlights persistent inefficiencies in Pakistan's agricultural water use. Yields for most crops lag behind world averages, while water consumption per unit of output is considerably higher, especially for rice, maize, sugar, fruits, and vegetables. The high reliance on blue water resources further exacerbates pressure on already stressed surface and groundwater systems. Although cotton lint exhibits relatively higher economic returns per unit of water, Pakistan remains a net importer of cotton-related virtual water, reflecting structural constraints in productivity and competitiveness. At the international level, Pakistan exported large volumes of virtual water through rice, fruits, and vegetables, while importing virtual water mainly via cotton lint and wheat. These trade patterns suggest that Pakistan continues to export water-intensive commodities despite domestic water scarcity, raising concerns about the long-term sustainability of current cropping and trade choices. Overall, the findings highlights that virtual water trade in Pakistan is driven more by market forces and historical cropping patterns than by considerations of water-use efficiency or resource sustainability. The higher percentage of blue water consumption is also a serious threat to Pakistan's overtime depleting water resources. It is suggested that clustering agricultural commodities based on each province's comparative advantage should be encouraged. Additionally, maximizing value generation per unit of water use is essential to make the best use of the available water resources in each province. Low-water availability regions need to specialize in high-value crops that could be exported to other provinces as well as in international markets. In conclusion, unsustainable consumption, over-extraction, and changing climate have put additional pressure on water use sustainability in Pakistan. Therefore, it requires proper attention to make virtual water trade across the provinces and globally worthwhile.

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Novelity Statement

The latest analysis of the virtual water trade with its implications for water resources was absent in country, hence, there was a dire need for such research. In this research study virtual water trade is analyzed based on the data available from secondary sources for the area, production, consumption, and water use for major crops, fruits, and vegetables. We declare this manuscript is original, has not been published before and is not currently being considered for publication elsewhere. The authors declared that there were no conflicts of interest associated with this publication.