

Article

Sustainable Water Use for International Agricultural Trade: The Case of Pakistan

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Abstract: Sustainable use of resources is critical, not only for people but for the whole planet. This is especially so for freshwater, which in many ways determines the food security and long-term development of nations. Here, we use virtual water trade to analyze the sustainability of water used by Pakistan in the international trade of 15 major agricultural commodities between 1990 and 2016 and in 2030. Most of the existing country-level studies on virtual water trade focused on net virtual water importers, which are usually water-scarce countries as well. This is the first study to concentrate on a water-stressed net virtual water-exporting country. Our results show that Pakistan has been trading large and ever-increasing volumes of virtual water through agricultural commodities. Despite the overall small net export of total virtual water per year, Pakistan has been a net-exporter of large quantities of blue (fresh) virtual water through its trade, even by fetching a lower value for each unit of blue water exported. Given Pakistan's looming water scarcity, exporting large volumes of blue virtual water may constrain the country's food security and long-term economic development. Improving water use efficiency for the current export commodities, for example, rice and exploring less water-intensive commodities, for example, fruits and vegetables, for export purposes can help Pakistan achieve sustainable water use in the future.

Keywords: sustainability; agriculture; virtual water trade; blue; green

1. Introduction

Sustainable development, as defined by the United Nations, is “development that meets the needs of the present without compromising the ability of future generations to meet their own needs” [1]. As an essential primary natural resource, the role of water in sustainable development is well recognized due to its critical functions in social and economic activities [2]. Unsustainable use of freshwater resources by nations can hamper their food security and long-term economic development [3]. The future water vision emphasizes that by 2050, “global markets and trade flows would be monitored through a global water sensitivity certification scheme that ensures water-intensive products are exported from areas with comparatively little or no water stress. We will recognize the economic value of water and all forms of an economic enterprise will take consideration of the water implications of their actions” [2]. Virtual water trade (VWT) can be used to gauge the water that is virtually transferred from one region to another region through commodities and services, both at global and national levels.

Nations can ensure the sustainable use of domestic freshwater by prioritizing their production and trade decisions based on water availability. Trade in virtual water is the amount of hidden/virtual

water that crosses borders with commodities/services. Virtual water content (VWC), defined as the ratio of the total water used for the production of the crop to the total volume of crop produced (m^3/ton), is a crucial concept used in the relevant literature [4]. The virtual water content of primary crops is calculated based on crop water requirements and yields [4]. Several studies have demonstrated the role of virtual water trade in ameliorating regional water shortages. Chapagain et al. [5,6] found that virtual water trade saved 6% of global agricultural water use. More recently, References [7–10] demonstrated the role of virtual water in improving water use efficiency and saving global water resources. Several national-level studies have also shown that water-scarce countries have used VWT to alleviate pressure on domestic water resources by importing water-intensive products [11–18]. In his seminal studies on virtual water, Allan [19,20] discussed how the Middle Eastern countries were able to overcome national water shortages through cereal imports. Many other important studies on Brazil, China, Cyprus, Egypt, the Middle East, Morocco, Spain and Tunisia also show the role of VWT in saving (and losses, if any) of domestic water resources for these countries [11–14,21–29].

Pakistan—with the world's fifth-largest population [30]—is a water-stressed country and its freshwater resources face heightened pressure from increasing population and climate change [31]. With an average annual rainfall of about 250 mm, Pakistan is among the most arid countries of the world [32]. Relying upon the most extensive contiguous irrigation system in the world, Pakistan uses over 94% of national water withdrawal in agriculture [33]. In the past, the country failed to add any large water reservoirs, thus adding to the pressure on dwindling water resources, especially in agriculture [34]. Due to declining per capita availability of water, Pakistan will turn from currently water-stressed to a water-scarce country in the 2040s [31]. Groundwater depletion due to unsustainable use of the aquifers for agriculture is becoming more severe in Pakistan [35]. Moreover, increasing quantities of pesticides and fertilizers used in agriculture are causing large-scale uncontrolled pollution of surface and groundwater [31].

Agriculture, the most water-intensive sector in Pakistan, can be taken as the strongest candidate to overcome the growing national water scarcity. Over 26% of crop-related groundwater depletion in Pakistan is due to crops exported to other countries, the majority of which (82%) is embedded in rice exports [35]. Although several studies have discussed the relevance of virtual water in agricultural trade for Pakistan [6,35–38], most of these studies either fail to distinguish between blue and green water (the blue water includes surface water and groundwater, while the green water is the rainwater stored in the soil as soil moisture [37]) or are related to domestic production/consumption of blue/green water. Chapagain et al. [6] report net savings of Pakistan's water resources through the international trade of all major crops and livestock products. However, the study is limited with respect to reporting only point analysis (average for 1997–2001) and reporting only total water savings. Dalin et al. [35] show that Pakistan is facing groundwater depletion through the international food trade. Although an influential study, it is limited to groundwater and presents its analysis only for two years, that is 2000 and 2010. The study by Fraiture et al. [36] shows net water savings for Pakistan. The study only covers total water savings through the cereal trade in 1995. Chapagain and Hoekstra [37] report blue, green and greywater impacts of international trade of rice for Pakistan and other countries for the period 2000–2004. This study, however, lacks a temporal analysis and the coverage of other agricultural commodities. The green, blue and grey water footprint of global crop production, including that of Pakistan, are covered in Reference [38]; however, no trade analysis is presented in the study. Pakistan's high dependence on freshwater for agriculture production, dwindling water resources and increasing trade in agriculture should be a strong motivation for conducting a more detailed study on trade in virtual water for Pakistan.

The primary purpose of this study is to assess the evolution of trade and savings/losses of Pakistan's blue and green virtual water through international trade of the agricultural commodities during 1990–2016 and in 2030. By doing so, we can answer the following research questions: What are the major commodities and source/destination regions involved in Pakistan's VWT? How Pakistan's VWT has evolved over the years and which policies have driven the changes in VWT? More importantly,

was the trade dominated by blue or green virtual water? Has Pakistan been saving blue/green water through its trade in agricultural commodities at the national and global levels? Has Pakistan's trade in blue and green VW been economically viable over the years? How would the trends evolve in the future? What is the value of the virtual water contents of these agricultural commodities? A detailed analysis of historical and future blue and green virtual water movements through Pakistan's global agricultural trade can help policy planning on water use for the country. To the best of our knowledge, this is also the first study focused on a water-stressed country that exports large quantities of agricultural products and virtual water.

The rest of the paper is organized as follows. Section 2 describes the methods and data used in this study. Section 3 presents our results on virtual water contents of these commodities for Pakistan; and trade and net savings/losses in terms of total, blue and green virtual water over the past years and in the future. Section 4 discusses the implications of our results and presents policy and research recommendations. The Section 5 presents the conclusions.

2. Materials and Methods

2.1. Selection of Agricultural Commodities

We selected 15 agricultural commodities to display a representative profile of international trade of virtual water for Pakistan. The crops include rice, wheat, maize, cotton, fruits, vegetables (See Appendix A for the complete list of fruits and vegetables included for the analysis), tea, tobacco, oilseeds (soybean, sunflower, groundnuts, copra, rapeseed and cottonseed), other cereals (rye, barley, oats, sorghum and millets), sugar and palm oil. The livestock commodities include the meat of bovine animals (beef), the meat of sheep or goat (mutton) and poultry meat. On average, these crops accounted for over 90% of the harvested area in Pakistan during 1990–2016. Beef, mutton and poultry meat provide over 81% of the animal source protein to consumers in Pakistan [39]. In terms of trade value, all of these commodities account for around 80% of export value and 93% of the import value of Pakistan's total annual agricultural exports and imports, respectively [40].

2.2. Projections of Pakistan's Agricultural Trade in 2030

To estimate the future impacts of Pakistan's agricultural trade on the country's water resources and global savings, we make use of the Global Trade Analysis Project (GTAP) model and its latest database (with the base year 2011) to project Pakistan's trade through to 2030. GTAP is a well-known and widely used global general equilibrium economic model [41,42]. The model assumes cost minimization by producers and utility maximization by consumers. In a competitive market setup, prices adjust until supplies and demands of all commodities equalize. The model and database have been extensively used in research areas such as food security policy, energy, climate change, poverty and migration, among others. There are other model choices as well, like ENVISAGE, FARM, GTEM, AIM and MAGNET, GLOBIOM, GCAM and IMPACT. Most of these computable general equilibrium (CGE) models have their roots in the Global Trade Analysis Project database and the CGE optimizing approach [41] and so have similar model specifications. They mainly differ in parameterization choices, which significantly affect the result. Nelson et al. [43] have discussed the effects of model structure and parameter choice on the results of CGE simulations in detail.

For projecting the future trade of Pakistan with other countries, we use a recursive dynamic method wherein the given GDP targets are met by exogenous shocks to factors of production including population, skilled labor, unskilled labor, capital and natural resources. The exogenous macro assumptions and the procedure for implementing these shocks are discussed in detail in References [41,44], respectively. Most of the data used for projections are based on the CEPII EconMap database 2.4 (2016), which contains 1980–2050 and 2100 data for 167 countries and 6 scenarios (one central scenario and the 5 Shared Socioeconomic Pathways) for GDP, savings, investment, total

population, labor force, capital stock, total primary energy consumption, human capital, total factor productivity and energy efficiency [45].

For these projections, we retained maximum disaggregation for agricultural commodities and Pakistan's major trading partners. As for projection for future agriculture production in Pakistan, we use current production technology and the availability of irrigation water. The potential decrease in water availability for agricultural production in the coming decade due to climate change, population growth and urbanization could well be countered by the improved crop production technology (like drought-resistant varieties and new irrigation technology).

2.3. Virtual Water Contents

The virtual water trade between the country/region of production to the country/region of consumption through product trade is the volume of water that is being transferred in virtual form. In this study, the virtual water flows related to Pakistan's agricultural trade have been calculated by multiplying commodity trade flows (ton/year) by their associated virtual water content (m^3/ton). The virtual water content (VWC) of a commodity is the quantity of water required to produce one ton of crop biomass, estimated as Equation (1).

$$\text{VWC}_{i,g,t} = \frac{\text{ETTOTAL}_{i,g,t}}{\text{Yield}_{i,g,t}} \quad (1)$$

where *ETTOTAL* is the total evapotranspiration during the cropping period (m^3/ha); yield is crop yield (ton/ha) and *i*, *g*, *t* denote crop, grid cell and year, respectively. *ETTOTAL* is further formulated as follows:

$$\text{ETTOTAL}_{i,g,t} = \sum_{\text{doy}=p}^h \text{ET}_{c,g,\text{doy}} \quad (2)$$

where ET is daily evapotranspiration ($\text{m}^3 \text{ ha}^{-1} \text{ day}^{-1}$) and *doy*, *p* and *h* denote the day of year, the planting date and the harvesting date, respectively. *ETTOTAL* is divided into blue and green water as follows:

$$\text{ETTOTAL}_{i,g,t} = \text{ETTOTAL}_{\text{BLUE},i,g,t} + \text{ETTOTAL}_{\text{GREEN},i,g,t} \quad (3)$$

Based on the type of water used in *ETTOTAL*, VWC can be split into green and blue types, where green and blue water in the context of VW are water consumed by crop vegetation that originated from precipitation and irrigation, respectively [46]. Blue and green VWC have substantially different opportunity costs associated with them (for a more detailed discussion of the method see Hanasaki [46]). Pakistan's virtual water export is the volume of water used to produce export commodities. Similarly, the virtual water import of Pakistan is the volume of water used to produce commodities in the trading partners imported by Pakistan.

The data on VWC of rice, wheat, maize, beef, mutton and poultry are taken from Reference [46] throughout 1990–2005. The original data in the study [46] are based on the H08 model and runs from 1986 to 2005 (The data can be downloaded from the link: <https://sites.google.com/site/naotahanasaki/english-contents/data/vwc>). Here, we note that in the absence of national estimates of virtual water contents, our study uses assessments from global models, which might contain discrepancies in the results due to the differences in modelling assumptions, input data and parameters adopted by local and global models (see Zoumides et al. [47] for a detailed discussion of these discrepancies). For the period after 2005, where VWC data are unavailable, we make use of the finding that VWC (or water productivity) has a strong inverse (or direct) relationship with crop yield [22]. This method has also been used in other studies like [8,48,49]. Specifically, we employ yield data from Reference [39] in Equation (4) to update the country-specific VWC of these crops and livestock as:

$$\text{VWC}_{w,i,r,t} = \text{VWC}_{w,i,r,2005} \times Y_{w,i,r,2005} / Y_{w,i,r,t} \quad (4)$$

where w represents water type (blue and green), i denotes commodity, r means country/region and t represents the years, that is, 2006 to 2016.

For updating the VWC for livestock sectors, we extrapolated the VWC values from Reference [46] to future years by assuming a 1% improvement in water productivity every five years for livestock production, which is in the spirit of Reference [27]. For fruits and vegetables, we used VWC for apples and tomatoes, respectively, from Reference [10], which is also in the spirit of Reference [50], which used VWC for apples and tomatoes as representative crops for fruits and vegetables, respectively. The VWC for cotton, palm oil, tea, tobacco, other cereals and oilseeds are from Reference [10], who reported country-wise blue and green VWC of these crops for the period 1996–2005. We applied the method described in Equation (3) to update respective VWCs.

For the future VWC values of rice, wheat, maize, cotton, tea, tobacco, oilseeds, other cereals, sugar and palm oil, from 2017 to 2030, we make use of the forecasts on water productivity from Reference [51]. The study uses IMPACT-WATER model to examine water and food policy and investment issues. Based on the assumptions of enhancements in area and yield growth; decrease in water consumption per hectare and improvement in water supply between 1995 and 2025, the study suggests that over the 30 years, the water productivity of non-rice cereals will improve by 66% (from 0.6 to 1.0 kg/m³) for developing countries and 40% (from 1.0 to 1.4 kg/m³) for developed countries. The water productivity for irrigated rice is projected to increase by 33% and 10% for developing and developed countries, respectively. We used these figures to estimate the average annual improvement in the water productivities for developing and developed countries (e.g., 66/30 = 2.2% per annum improvement in water productivity for developing countries) and then the annual change in country-specific VWCs for all the crops mentioned above. The future values of VWC for fruits and vegetables were updated by incorporating 0.5% yearly improvement in water productivity; which is based on [27]. Table 1 contains a full summary of the sources and assumptions for the VWC values used in this study for all the commodities over various periods.

Table 1. Summary of sources and assumptions used for virtual water content (VWC) data.

Commodity	Period	Reference	Assumptions/Recalculations
Rice, wheat, maize, beef, mutton and poultry	1990–2005	[46]	Unprocessed data
Rice, wheat and maize	2006–2016	[22,46]	Recalculated VWC based on the inverse relationship between VWC and crop yield
Fruits and vegetables	1996–2005	[10]	Unprocessed values for apples (for fruits) and tomatoes (for vegetables)
Cotton, palm oil, tea, tobacco, other cereals and oilseeds	1996–2005	[10]	Unprocessed data
Cotton, palm oil, tea, tobacco, other cereals, oilseeds, fruits and vegetables	1990–1995 and 2006–2016	[10,22]	Recalculated VWC based on the inverse relationship between VWC and crop yield
Rice, wheat, maize, cotton, tea, tobacco, oilseeds, other cereals sugar and palm oil	2017–2030	[10,46,51]	Recalculated VWC values by estimating the annual improvement in the water productivities for developing and developed countries based on the forecasts on water productivity from Reference [51]
Fruits and vegetables	2017–2030	[10]	Assumed 0.5% annual improvement in water productivity
Beef, mutton and poultry	2006–2030	[46]	Assumed 1% improvement in water productivity every five years for livestock production based on the values from Reference [46]

2.4. Virtual Water Flows

We calculated the virtual water imports ($VWI_{w,i,r,t}$) and virtual water exports ($VWE_{w,i,r,t}$) of Pakistan for both blue and green water by multiplying the blue and green VWC with import and export quantities of the commodities, as follows:

$$VWI_{w,i,r,t} = M_{i,r,t} \times VWC_{w,i,r,t} \quad (5)$$

$$VWE_{w,i,r,t} = X_{i,r,t} \times VWC_{w,i,PAK,t} \quad (6)$$

where $M_{i,r,t}$ denotes the quantity of commodity i imported by Pakistan from country/region r during year t . $X_{i,r,t}$ represents Pakistan's export of commodity i to destination r in year t . $VWC_{w,i,r,t}$ is the partner countries' virtual water content (blue and green) of the particular commodity in the respective year (unit: m^3/ton). $VWC_{w,i,PAK,t}$ is Pakistan's virtual water content (blue and green) of the particular commodity in the respective year (unit: m^3/ton). Subtracting VWE from VWI gives us net virtual water imports (NVWI) of Pakistan, as under:

$$NVWI_{w,i,PAK,t} = VWI_{w,i,r,t} - VWE_{w,i,r,t} \quad (7)$$

Pakistan's domestic saving of blue/green water ($DSAV_{w,i,PAK,t}$) through imported commodities is the amount of blue/green water needed to produce the same commodities at home. This is estimated by replacing $VWC_{w,i,r,t}$ of the partner country, with $VWC_{w,i,PAK,t}$ of Pakistan in Equation (5) and then using it in Equation (7).

Pakistan can also contribute to global water saving if it saves more domestic water ($DSAV_{w,i,PAK,t}$) than its net virtual water import ($NVWI_{w,i,PAK,t}$). Specifically, the global saving (or loss) of blue and green water is the difference between the amount of water which Pakistan saves domestically through its food trade and the amount of $NVWI_{w,i,PAK,t}$, which it imports from other countries Equation (8).

$$GSAV_{w,i,t} = DSAV_{w,i,PAK,t} - NVWI_{w,i,PAK,t} \quad (8)$$

Pakistan's food trade would save (waste) water at the global level if we get a positive (negative) value from Equation (8). Total national and global water savings are the sum of respective savings from all commodities and all trading partners.

2.5. Value of Virtual Water Flows

The value produced by one unit of water (value of virtual water, i.e., VVW) is an important indicator of the efficiency of water use in different sectors (unit: $\text{US}\$/\text{m}^3$) (the average exchange rate over the period 1990–2016 was 1 $\text{US}\$ = 60.4$ Pakistan Rupee [39]). Due to the differences in the opportunity costs of green and blues water, we calculate an average value of blue virtual water of the studied commodities over 1990–2016 by dividing the production value (unit: $\text{US}\$/\text{ton}$) by the blue VWC (unit: m^3/ton) that is

$$VVW_{i,t} = NPV_{i,t} / BVWC_{i,t} \quad (9)$$

where $VVW_{i,t}$ is value produced by one unit of blue water by commodity i in year t ($\text{US}\$/\text{m}^3$), $NPV_{i,t}$ is the net production (it is the value of net production, where, Net production = Production—Feed—Seed [39]) value of each commodity i produced in year t and $BVWC_{i,t}$ is the blue virtual water content of each commodity i produced in year t . The values for $NPV_{i,t}$ for Pakistan are obtained from Reference [39], while $BVWC_{i,t}$ values are based on various sources described earlier in this section.

3. Results

3.1. Virtual Water Contents of the Commodities

We start with a brief background on the importance of each crop in Pakistan's agriculture by comparing its harvested area to the total harvested area (Table 2) (Appendix A contains a more detailed analysis of Pakistan's agricultural trade; Figures A1 and A2). The analysis shows that crop harvested area in Pakistan is dominated by wheat (42%), seed cotton (14%), rice (12%) and sugar crops (5%) during 1990–2016 (Table 2). Table 2 also compares Pakistan's average yields of the agricultural commodities with global average yields during 1990–2016 (columns 2–3). Except for tobacco (where Pakistan produces a higher yield than many other countries) and cotton lint (where yield in Pakistan is equal to global yield), Pakistan's yields of all the commodities are considerably lower than the corresponding global averages. The yield gap is significantly higher for two crop groups, that is, other cereals and oilseed crops, where yields in Pakistan are 11% and 36% of the global average yields over this period. For livestock production, Pakistan's yield (kg/animal) of mutton (goat and sheep meat) and poultry (chicken meat) are relatively close to the global averages, whereas beef (buffalo and cattle meat) yield is also significantly (39%) lower than the worldwide level. The small agricultural yields are mainly due to poor irrigation water management, lack of advanced methods and quality inputs, fragmented land holdings and inadequate institutional support to the farmers. The relative lower yields of most of the commodities show that agricultural productivity in Pakistan can be substantially improved, which, due to an inverse relationship with VWC, can lower VWC for these commodities. In the absence of such productivity improvements, Pakistan will face the challenge of reducing agricultural exports or increased pressure on water resources.

Table 2. Average shares in total harvest area, yields and virtual water content (blue, green, total, ratios of blue/green) of major agricultural commodities produced in Pakistan (1990–2016).

Commodities	Share in Total Harvested Area (%)	Yield ¹		VWC (m ³ /ton)			Share of Blue VWC in Total VWC (%)
		Pakistan	World	Blue	Green	Total	
Wheat	41.7	2.4	2.8	1603	260	1862	86.1
Cotton lint ²	14.4	1.9	1.9	2781	4193	6974	39.9
Rice	12.0	3.1	4.0	2370	576	2947	80.4
Sugar unrefined ³	5.1	5.4	7.3	2309	577	2887	80.0
Maize	4.9	2.6	4.6	1048	1150	2198	47.7
Other cereals	3.9	2.1	19.4	1048	1150	2198	47.7
Fruits	3.6	8.9	11.1	499	599	1098	45.4
Oilseed crops	2.6	4.2	11.4	617	1536	2153	28.7
Vegetables	2.6	12.7	16.6	371	120	491	75.6
Tobacco ⁴	0.3	2.0	1.7	1052	1315	1315	80.0
Palm oil	0.0	-	12.2	0	4833	4833	0.0
Tea	0.0	-	1.4	9	8727	8735	0.1
Beef	-	147.2	204.5	11,713	6871	18,584	63.0
Mutton	-	16.5	14.3	5021	2955	7976	63.0
Poultry	-	1.1	1.6	4100	1388	5487	74.7

¹ Crop yields are in tons/ha; meat yields are kg/animal. ² Share in harvested area is for seed cotton. ³ Share in harvested area is for both sugarcane and sugar beet. ⁴ Unmanufactured tobacco. Source: Authors' calculations based on data from Reference [39] (trade volumes) and sources mentioned in the Methods section (VWC).

VWC for the studied agricultural commodities changes with the yearly fluctuation in yield of each commodity. Although annual blue and green VWCs were used for estimating the trade in virtual water in respective years, we report the average VWC (over 1990–2016) for all the commodities (Table 2). The total virtual water contents for the crops vary widely from 491 m³/ton for vegetables to as high as 6974 m³/ton for cotton lint (Table 2, column 6). The VWC for livestock sectors is far higher than the ones for crops, ranging between 5487 m³/ton for poultry to 18,584 m³/ton for beef. Except for oilseed crops, palm oil and tea, blue VWC constitutes much higher shares in the total VWC for both crops and

livestock sectors. Notably, for the major crops (wheat, rice and sugar) the percentage of blue VWC in the total VWC ranges between 80% and 86%, indicating very high dependence of these crops on irrigation in Pakistan. The analysis shows that the efforts aimed at improving yields and lowering VWC can significantly lower irrigation water requirements for agricultural commodities in Pakistan.

3.2. Total Virtual Water Trade

Pakistan's annual total virtual water import, although with some inter-annual fluctuations, grew at an annual average rate of 5% between 1990 and 2016 (Figure 1, the sum of yearly points along the red lines). The yearly average of total virtual water import was 8216 million m³ (Mm³), 11,218 Mm³ and 12,202 Mm³ during the periods 1990–1999, 2000–2009 and 2010–2016, respectively. The annual total virtual water import through agricultural commodities by Pakistan dropped significantly after 2008, from 17,799 Mm³ in 2008 to 10,257 Mm³ in 2011, after which it started to increase again. The drop in total virtual water import between 2008 and 2011 was mainly due to a decrease in imports of cotton lint by Pakistan.

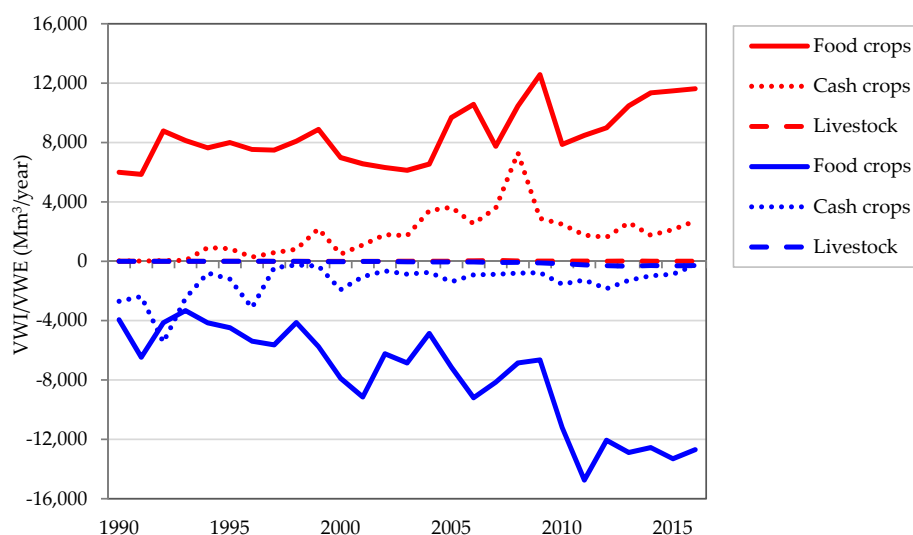


Figure 1. Virtual water import (VWI) and virtual water export (VWE) of different agricultural commodities by Pakistan (1990–2016). Red lines indicate VWI and blue lines indicate VWE. Food crops include rice, wheat, maize, other cereals, oilseed crops, palm oil, sugar, vegetables, fruits and tea; Cash crops include cotton and tobacco; Livestock includes beef, mutton and poultry. Source: Authors' calculations based on data from Reference [39] (trade volumes) and sources mentioned in the Methods section (VWC).

The annual total virtual water exports through the agricultural commodities (Figure 1, the sum of yearly points along the blue lines), however, saw a more rapid and steady increase over the years. Starting at an average of 6663 Mm³/year during 1990–1999, the total virtual water export moved to an average 8345 Mm³/year during 2000–2009 and reached 14,205 Mm³/year during 2010–2016; thus, recording a 113% increase over the period 1990–2016. Food crops (mainly rice) exports were responsible for the rise in Pakistan's total virtual water export.

During the study period, Pakistan's virtual water import (VWI) and virtual water export (VWE) have been dominated by trade in food crops (Figure 1). On average, food crops accounted for over 82% of the total VWI and over 84% of the VWE by the studied commodities. Not only the share of food crops in VWE was higher, but the VWE of food crops has also been increasing rapidly since 2005. VWI of cash crops was low in the early 1990s, after which it started to rise and reached the historical peak (7308 Mm³) in 2008, before sliding down to a relatively lower level in the later years. During 2008, VWI through cash crops increased mainly due to a sharp rise in imports of cotton by Pakistan. VWI and VWE of livestock have been marginal, with VWE picking up some pace since the early 2000s.

3.3. Pakistan's Net Virtual Water Import

3.3.1. Total Net Virtual Water Import

During 1990–2016, Pakistan's total net virtual water import through the studied commodities has been fluctuating widely from the negative end to the positive end (Figure 2). During 1990–1999, the average annual total net virtual water import remained quite low ($1553 \text{ Mm}^3/\text{year}$); after that, it increased continuously to reach a historical peak of $10,075 \text{ Mm}^3$ in 2008. Since then, it saw a sharp decline to reach a historic low of -5998 Mm^3 in 2011 and remained negative in most of the later years. Over the years, the evolution of total net virtual water import (with an annual average of mere 1120 Mm^3) seems to indicate that Pakistan has gained some quantities of virtual water through its trade in the major agricultural commodities during 1990–2016. However, further bifurcating total net virtual water import into blue net virtual water import and green net virtual water import would reveal further insights into Pakistan's trade of virtual water, which we present in the next sub-section.

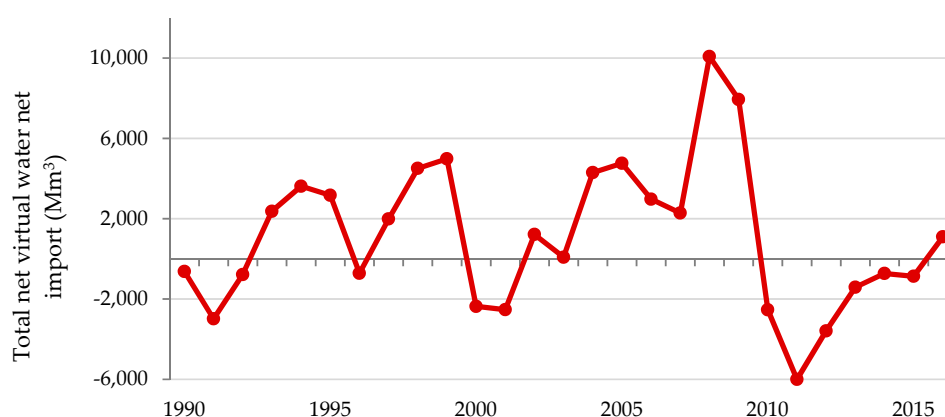


Figure 2. Evolution of Pakistan's total net import of virtual (1990–2016). Source: Authors' calculations based on data from Reference [39] (trade volumes) and sources mentioned in the Methods section (VWC). Cotton also contributed significantly towards Pakistan's blue net virtual water import over the years. For cotton, blue net virtual water import was mostly negative during 1990–2001, after which it turned positive, that is, Pakistan became a net importer of cotton from a net exporter after 2001 (Figure 3a). The reason was increased demand for high-grade cotton by Pakistan's domestic industry, which was not met by the domestic production of cotton, due to lower production in some years and lower quality in others [52,53].

3.3.2. Commodity-Wise Net Import of Blue and Green Virtual Water

The commodity-wise contribution of net VWI of blue and green water varies considerably in Pakistan (Figure 3). Wherein, blue net virtual water import was mostly negative and green net virtual water import was mostly positive. Pakistan's negative blue net virtual water import has been mostly dominated by blue net virtual water import via rice exports, which had an average annual blue net virtual water import of -5680 Mm^3 and accounted for an average share of 94% in the total annual blue net virtual water import over the study period (Figure 3a). Moreover, blue net virtual water import through rice has been rising over the years; from an annual average of -3547 Mm^3 over 1990–1999 it increased to -5271 Mm^3 per annum during 2000–2009 and reached -9314 Mm^3 per year during 2010–2016. The rise in negative net VWI through rice can be attributed to rising domestic production and decreasing share of domestic consumption of rice in the domestic production in Pakistan. Specifically, rice production in Pakistan increased at a rate of 4.3% per year, from 4.89 million tons in 1990 to 10.5 million tons in 2016. Both yield and area contributed to improving production [39]. The combined effect of these factors was a steady year-on-year increase in rice exports from Pakistan. So much so that during 2010, Pakistan exported a staggering 86% of the domestically produced rice to the international market [39].

The contribution of wheat trade towards blue net virtual water import of Pakistan, although relatively small, saw an unusual feature over the study period. During 1990–1999, blue net virtual water import due to wheat had been consistently positive due to the small but sustained net import of wheat by Pakistan. After 1999, however, Pakistan occasionally recorded negative net import of wheat, which lead to sizable negative contributions to the total blue net virtual water import of Pakistan. The reason for this fluctuation in blue net virtual water import through wheat trade over the years was lower production in some years or bumper crops in others and due to weather events and poor stock management [54,55].

The blue net virtual water import of Pakistan due to the rest of the crops like maize, other cereals, oilseed crops, palm oil, sugar, vegetables, fruits, tea and tobacco and livestock such as beef, mutton and poultry has been quite small over the study period (Figure 3a).

Several agricultural commodities have contributed towards green net virtual water import, of which the total contributions due to net imports of palm oil, tea, wheat, oilseeds and cotton have been positive, that is, Pakistan imported more green VW through the trade of these crops than it exported (Figure 3b). Palm oil, with the average yearly contribution of 89% (5465 Mm³/year), was the most dominant commodity. Interestingly, in some years like 1992 and 1999, the contribution of wheat towards green net VWI even surpassed the share of palm oil due to large volumes of wheat imports by Pakistan. Green net virtual water import due to rice trade was negative over the study period. The rest of the crops and livestock had small but predominantly negative green net virtual water imports.

The comparison between both panels of Figure 3 indicates that Pakistan has been exporting ever-increasing quantities of blue virtual water, while at the same time importing almost equal amounts of green virtual water, which in the end seems to have canceled out the effects on Pakistan's water resources. However, the transfer of blue virtual water to other countries through net virtual water export is far more valuable than the green virtual water transfers from other countries into Pakistan through net virtual water import.

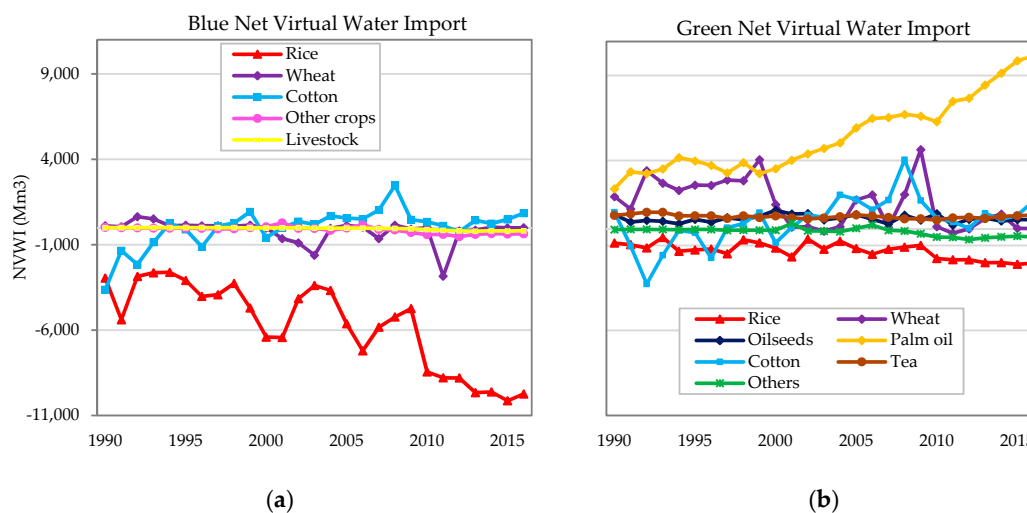


Figure 3. Commodity-wise evolution of (a) blue and (b) green net virtual water import of Pakistan (1990–2016). Source: Authors' calculations based on data from Reference [39] (trade volumes) and sources mentioned in the Methods section (VWC).

Blue water is far more costly than the green water used for agricultural production; as for the former, there are considerable costs in terms of construction, maintenance and operation of dams and the related irrigation systems, which are usually born by the citizens of exporting countries. However, these costs are not adequately included in the price of blue water or reflected in the price of final products. In addition to economic costs, there are many environmental and social costs of ensuring steady supplies of blue water, which are seldom considered in the literature of virtual water trade.

Exporting commodities heavily laden with blue water also reduces the domestic supply of this precious natural resource, intensifying any water shortage issues.

3.3.3. Region-Wise Net Virtual Water Import

In terms of regional distribution, Pakistan's negative blue net virtual water import (i.e., net blue virtual water export) has been destined mostly to Asian countries—mainly through rice export to Afghanistan, UAE and Iran- and African countries, also primarily via rice export to Kenya and Mozambique. Exports to both the Asian and African regions were responsible for annual blue net virtual water import of -3579 Mm^3 and -2042 Mm^3 , respectively, during 1990–2016 (Figure 4a). The share of blue net virtual water import from Asian countries in the total blue net virtual water import decreased from 67% during 1990–2010 to 53% during 2009–2016. For African countries, on the other hand, the share of blue net virtual water imports increased from 27% during 1990–2008 to 42% during 2009–2016. This indicates a gradual shift of Pakistan's export away from destinations in Asia towards African countries. European countries accounted for relatively small but constant share (9%) in the annual blue net virtual water import. North American and South American countries have registered positive (although small) contributions towards Pakistan's blue net virtual water import.

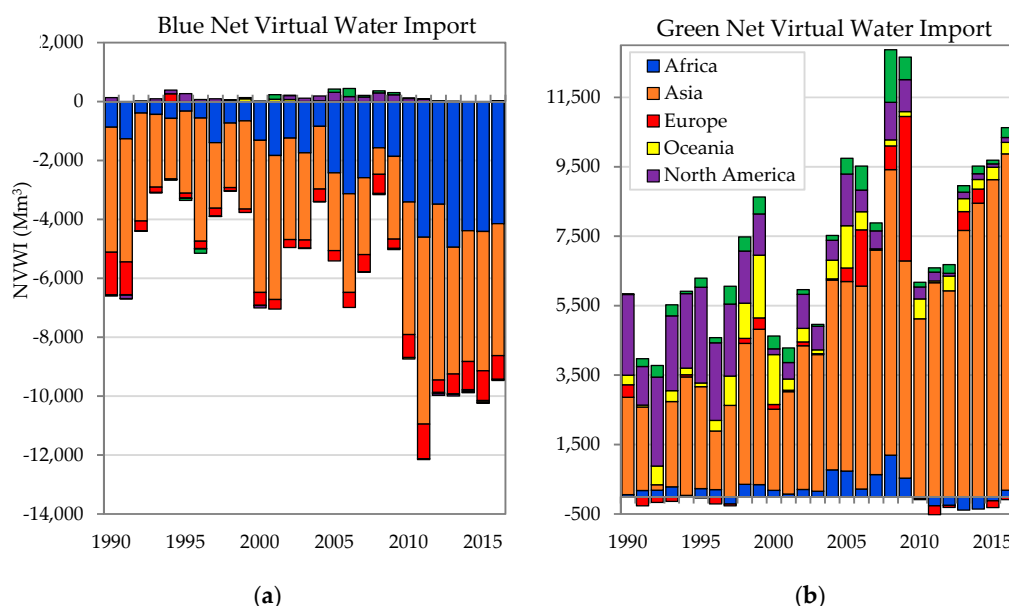


Figure 4. Region-wise evolution of (a) blue and (b) green net virtual water import of Pakistan (1990–2016). Source: Authors' calculations based on data from Reference [39] (trade volumes) and sources mentioned in the Methods section (VWC). In the period 1990–2016, Pakistan's green net VWI related to agricultural commodities was dominated by Asian countries with $4824 \text{ Mm}^3/\text{year}$ (Figure 4b). About 67% share was due to palm oil imports from Malaysia and Indonesia. On the other hand, trade with countries like Afghanistan, Iran, Saudi Arabia and UAE contributed small but negative shares to green net VWI. We can observe a noticeable shift in sources of green net virtual water imports over the years, with a continuous increase in the share of Asian countries and a gradual decrease in the percentage of North American countries (Figure 4b). Asian countries' share in Pakistan's green net virtual water import increased from 45% ($2311 \text{ Mm}^3/\text{year}$) during 1990–1997 to 73% ($5882 \text{ Mm}^3/\text{year}$) during 1998–2016 at the expense of North America's share, which dropped from 42% ($2170 \text{ Mm}^3/\text{year}$) during 1990–1997 to 8% ($603 \text{ Mm}^3/\text{year}$) during 1998–2016. Two factors caused the shift, that is, shrinking imports of wheat from North America and increasing imports of palm oil and cotton from Asia (a brief discussion of the water resources and their use in Pakistan and its major trade partners is presented in Table A1 of the Appendix A).

3.4. Water Savings at National and Global Levels

3.4.1. Blue Virtual Water

Our results show that except for a few years, Pakistan has been losing domestic blue virtual water due to its trade in the agricultural commodities (Figure 5a). As Pakistan is a net exporter of blue virtual water, this result is not surprising for the country. The average annual losses during 1990–1999 were -248 Mm^3 and increased to -5956 Mm^3 during 2000–2016. The most substantial losses of blue water were recorded in 2011, with a historic high of -11890 Mm^3 . During that particular year, in addition to its traditional export, that is, rice, Pakistan also exported large quantities of wheat, which caused the blue water losses to surge. For comparison, the water loss was equivalent to 7% of the total irrigation water used in Pakistan during 2011. In other words, Pakistan's negative blue net virtual water import is exerting additional pressure on the country's dwindling water resources. There have also been some years when Pakistan saved domestic blue water due to its trade (Figure 5a). The positive contribution of net virtual water import towards Pakistan's domestic blue water saving during the 1990s was due to massive net imports of wheat and during the late 2000s due to sharp but occasional increase in net imports of cotton.

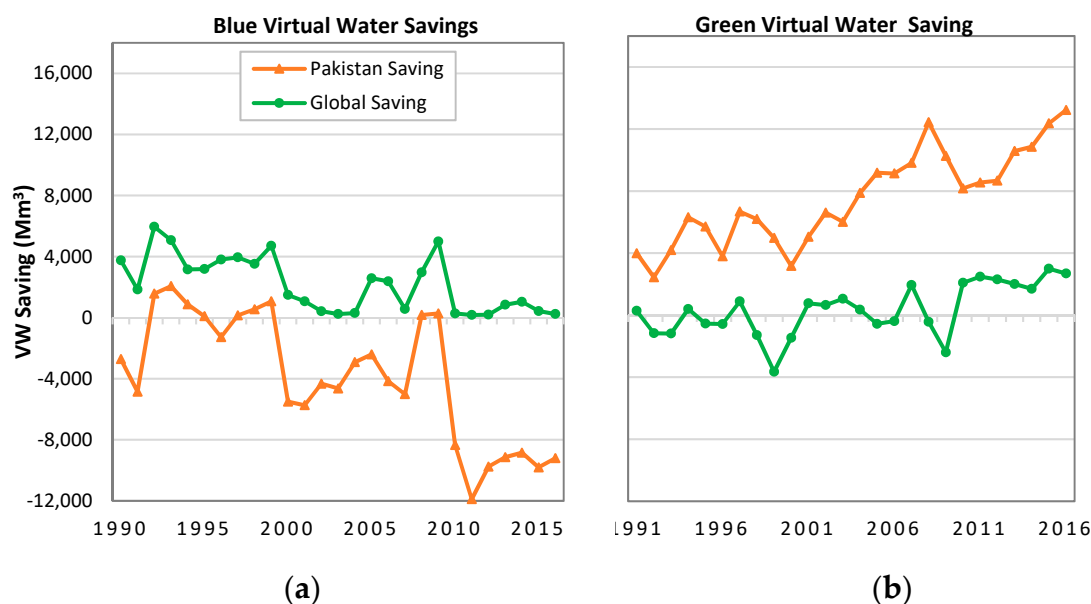


Figure 5. Evolution of (a) blue and (b) green water-saving for Pakistan and at global level (1990–2016). Source: Authors' calculations based on data from Reference [39] (trade volumes) and sources mentioned in the Methods section (VWC). At the global level, however, the average saving of green virtual water has been positive but small, that is, $307 \text{ Mm}^3/\text{year}$ (Figure 5b), mainly due to a relatively smaller difference between the green VWC of Pakistan and those of its import partners. The global saving of green virtual water has consistently been positive since 2010.

Pakistan's trade in the agricultural commodities has also contributed to sizable positive savings of blue virtual water at the global level (Figure 5a). This was due to Pakistan's higher blue water productivity in producing its imported commodities, especially those of wheat and cotton. The rate of global blue virtual water savings has been decreasing over the years, with $3896 \text{ Mm}^3/\text{year}$ blue VW global saving during 1990–1999, $1702 \text{ Mm}^3/\text{year}$ BVW global saving during 2000–2009 and $459 \text{ Mm}^3/\text{year}$ blue VW global saving during 2010–2016.

3.4.2. Green Virtual Water

Pakistan's domestic saving of green virtual water has been positive and increasing over the period 1990–2016, with an annual average of 7462 Mm^3 (Figure 5b). Starting with 5191 Mm^3 in 1990,

the domestic saving grew by 155% to 13,230 Mm³ in 2016. The (positive) domestic saving of green virtual water means that Pakistan would have needed an equivalent amount of extra domestic green water to produce the corresponding commodities (mostly palm oil, tea, cotton and wheat) domestically.

3.5. Pakistan's Virtual Water Trade in the Future

By 2030, Pakistan's trade and net imports of blue and green virtual water will increase quite significantly (Table 3). Pakistan's total net import of blue VW will remain negative and increase from −9446 Mm³ in 2016 to −29528 Mm³ in 2030, thus recording a 213% change (the figure in the parenthesis in the second row of Table 3) between 2016 and 2030. The net import of green VW during the same period will increase from 10,543 Mm³ in 2016 to 29,595 Mm³ in 2030. The ever-increasing quantities of rice exports will be the main factor behind the increase in (negative) net imports of blue VW for Pakistan in 2030. In contrast, cotton imports will contribute significantly to reducing the negative net import of blue VW in 2030. For green VW, on the other hand, the higher net import will be caused not only by the traditional import commodities like palm oil and tea but also by the positive net import of cotton by Pakistan in 2030.

Table 3. Pakistan's virtual water trade in 2030 (million m³).

Title	Green Water	Blue Water	Total
VW Import	37,012 (178) [†]	4013 (296)	41,025 (186)
VW Export	7418 (166)	33,541 (221)	40,959 (209)
VW Net Import	29,595 (181)	−29,528 (213)	66 (−94)
National Savings	40,471 (206)	−28,999 (215)	11,472 (185)
Global Savings	10,876 (305)	529 (121)	11,406 (290)

[†] The figures in the parenthesis are the percentage increase of the respective value in 2030 from the level in 2016.
Source: Authors' calculations

In 2030, the net import of VW through agricultural trade will save substantially more green virtual water but at the same time, cause much higher losses of blue VW for Pakistan (Table 3, row 4). The domestic saving of total VW for Pakistan will be 11,472 Mm³, a 185% increase from the 2016 savings of 4023 Mm³. Although the domestic savings of green VW will increase by 206% from 13,230 Mm³ in 2016 to 40,471 Mm³, however, the blue water losses will also increase, recording a 215% increase from −9207 Mm³ to −28,999 Mm³ over the same period. The trends show that the significant losses of blue VW for Pakistan will further expand in the future.

On the global scale, Pakistan's trade in agricultural commodities will have an overall positive impact in terms of total, blue and green virtual water savings in 2030 (Table 3, row 5). Specifically, Pakistan's agricultural trade in 2030 will save 11,406 Mm³ of the total virtual water, as compared to 2926 Mm³ in 2016 (a 290% increase). The contribution of green VW savings towards global VW savings from Pakistan's trade in agricultural commodities will be more than 20 times higher than the contribution from blue VW savings. Between 2016 and 2030, the global savings of green VW will increase 305% (from 2686 Mm³ to 10,876 Mm³), while that of blue VW will increase 121% (from 239 Mm³ to 529 Mm³). The detailed commodity-wise analysis (not shown in the table for space consideration) shows that with 12,180 Mm³ savings, palm oil will be the most significant contributor towards global savings of green VW. On the other hand, while the trade in the cotton crop will have a small positive contribution towards global savings of blue VW (398 Mm³), it will contribute negatively towards global savings of green VW (−1476 Mm³).

3.6. Value of Virtual Water Flows

The scatter plot between the value of virtual water (VW) and blue virtual water contents for Pakistan is shown in Figure 6. We can see that commodities like fruits, vegetables and oilseed crops, placed towards the bottom-right corner have high VW while they use relatively low blue water in their production, which means that these commodities use water more efficiently to produce higher economic value per unit of the blue water. On the other extreme is the beef sector, which uses large quantities of blue water to produce relatively low economic value. In comparison to other sectors, grain crops produced in Pakistan are not only less blue water-intensive but also produce lower economic output per unit of water. Interestingly, although the blue VWC of mutton and poultry are higher than the crops, their VW is even higher, making them more valuable commodities in terms of water use per unit of production as compared to crops.

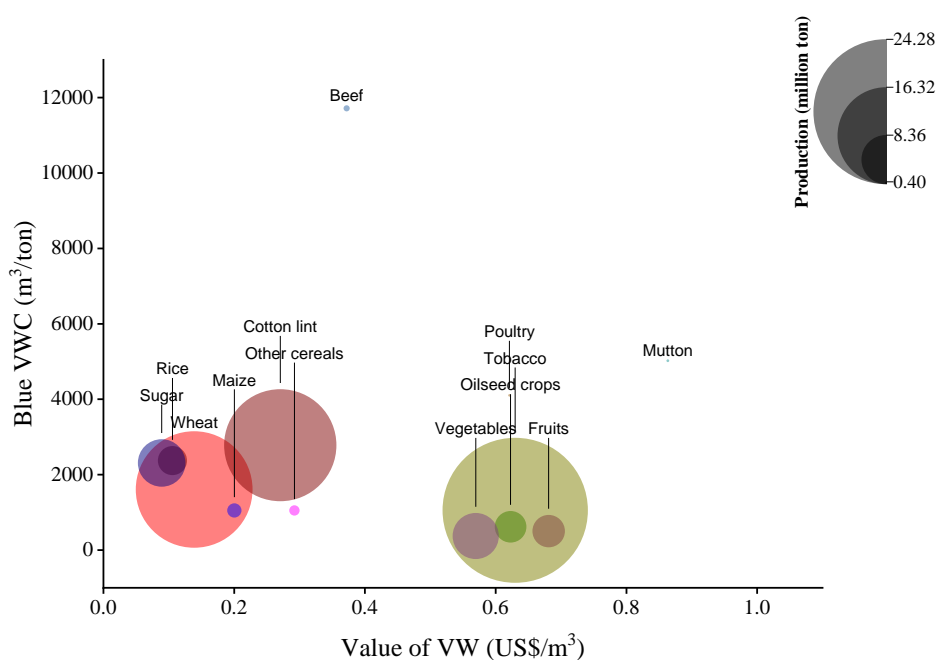


Figure 6. Average blue VWC and per unit water value for different agricultural commodities in Pakistan (1990–2016). 1 US\$ = 60.4 Pakistan Rupee over the period 1990–2016. Per unit water value is calculated based on Equation (9). Source: Authors' calculations based on data from Reference [39] (production value) and sources mentioned in the Methods section (VWC).

From the value of virtual water (VW) estimation, we can argue that to alleviate pressure on water resources and optimize blue water use in country's agriculture sector, Pakistan should promote the production of high-value and low-water-intensive commodities like vegetables, fruits and oilseeds. This type of structural adjustment will increase the value of output per drop of water. The optimization of water use for agricultural production should also consider other environmental aspects, like grey water footprint, especially for the livestock sectors.

4. Discussion and Policy Implications

The United Nations Sustainable Development Goal 12 highlights the need to pursue responsible consumption and production to address global environmental challenges such as water scarcity (Target 6.4 of Reference [56]). Pakistan, with water withdrawals for the agricultural sector of 94%, ranks among the highest in the world, compared to 69% at the global level [33]. Resolving water scarcity in developing countries like Pakistan could be achieved by focused research on the agricultural sector and the food system. In addition to devising localized, sustainable production and consumption systems,

the trade in agricultural commodities (through tele-consumption of food) can also play a crucial role in reducing water-scarcity at local and global levels.

Literature is available on the amount of virtual water traded between Pakistan and other countries, but there is a lack of research on Pakistan's blue and green virtual water trade, the relative economic value of blue and green virtual water and the implications for national and global water resources, especially the scarcer blue water. Also, the network properties of a Pakistan-centered virtual water trade network have never been analyzed. Differentiating the analysis into blue and green water components is particularly crucial because blue water has a higher opportunity cost [7] and different environmental effects than green water [57].

Similar to the earlier work in the field [7,58,59], we find that during the 1990–2016 period, Pakistan's total virtual water trade has been increasing. However, the net virtual water import has been small. Our future scenario of Pakistan's trade in agricultural commodities, however, shows that Pakistan will lose a significant amount of virtual water by 2030. At first glance, it appears that Pakistan's historical trade in agricultural commodities neither benefits nor harms the domestic water resources. However, once we separate virtual water trade into blue and green virtual water, we discover a large and increasing net export of blue water from Pakistan, which means that Pakistan indeed exported more expensive and scarce blue water. The future trade scenario shows that the losses of blue virtual water will further increase between 2016 and 2030. Our results clearly show the importance of considering the trade in blue and green water separately.

Our analysis shows that the unit value of blue virtual water export through rice crop (the dominant export crop) $0.10 \text{ US\$/m}^3$ has been lower than the corresponding value of green water import through palm oil (the dominant import crop) $0.15 \text{ US\$/m}^3$ during last the decade. This further demonstrates that, although unconsciously, Pakistan has not only been exporting its more precious water resource to other countries, it has been doing so by fetching a relatively lower price for the blue water export thus making the water trade even less economically viable. Moreover, the costs of constructing and running extensive irrigation infrastructure for the blue water used in agricultural exports further calls into question the actual benefits of exporting blue virtual water embodied in the commodities. One of the main reasons for these inefficient production and trade decisions is that farmers have been using irrigation water quite inefficiently in Pakistan [60], mainly due to subsidized irrigation water supply.

Pakistan's situation becomes even more worrisome when we consider the increasing scarcity of blue water in the country. Pakistan has been a net exporter of blue virtual water despite being a water-deficient country [61]. Other studies have shown that most of the water deficit countries have compensated for their domestic water scarcity by importing increasing imports of cereals [62,63]. The authors assert that upon reaching water availability of roughly $1500 \text{ m}^3/\text{capita}/\text{year}$, an inverse relationship can be identified between a country's cereal import and its per capita renewable water resources. Pakistan's annual water availability per inhabitant, which had already dropped to 1391 m^3 [33], is expected to reach around 800 m^3 by 2050 [64,65]. Looking ahead, the compounding water shortage in Pakistan would thus make the export of blue virtual water more unsustainable and questionable.

In contrast, the other water-stressed countries have been relying, although partially, on food imports to alleviate some pressure on domestic natural resources. For example, China's food trade saved $215.5 \text{ billion m}^3$ of domestic water in 2015, which was equivalent to about 55% of the country's irrigation water used in the same year [27]. Libya and Israel, having extremely scarce water resources, almost entirely rely on global markets for their cereal supply, with small domestic production [3]. Similarly, for Spain, higher net imports of virtual water during a dry year (8415 million m^3 in 2005) as compared to a wet year (3420 million m^3 in 1997) are consistent with the country's relative water scarcity [66]. These countries seem to have steered their domestic production and trade in agricultural commodities in line with the relative scarcity of water resources, which does not seem quite true for Pakistan.

A silver lining to Pakistan's net exports of domestic blue water resources is that Pakistan has induced a small but positive global saving of blue water over the years. The savings resulted from higher blue water use efficiency in the production of exported commodities (mostly rice) than the water use efficiency of the export destinations. The net imports of green water, on the other hand, saved considerable volumes of domestic green water for Pakistan, while there were quite modest global savings.

Our findings suggest that Pakistan has consistently engaged in exports of much scarcer blue VW, while the VW trade is often determined by factors other than water, like economic and political ones. Virtual water trade alone, therefore, cannot be taken as a yardstick to steer the trade and production policies. It is the combination of agricultural structure adjustment towards high water use-value commodities and active promotion of trade in these commodities that can optimize agricultural water use. By adopting such adjustments, Pakistan can also engage its rural labor force into agriculture, in which the country is better endowed than many other countries in the world [67,68]. Thus, Pakistan can not only make full use of its comparative international advantage in the production of labor-intensive commodities, such as fruits and vegetables [69] but also can save water by improved irrigation technologies, for example, drip irrigation and spray irrigation systems, which are more suitable for horticultural crops [70]. Our suggestion is also in line with the ones found in existing literature where the authors suggest that when water becomes a significant constraint and economic cost factor to agricultural production, improving per unit water value through agricultural structure adjustment is one of the rational options to increase water use efficiency and farmer's income [22].

Importantly, we do not take these results to argue that Pakistan should stop the production or export of blue water-intensive crops like rice. On the contrary, we suggest that the relative scarcity of blue water should be included in the production of agricultural commodities. Such policy measures will not only improve the domestic water use efficiency but will also increase the economic benefits of virtual water exports.

Although the notion of virtual water does not provide unambiguous conclusions about international trade efficiency from a water resources perspective, it might foster cooperation among countries for improving water and land management globally. This is especially relevant when considering adaptation to climate change, together with production and consumption patterns. Virtual water could, therefore, encourage discussions on transboundary water resource management strategies.

A few caveats of our study need to be highlighted here. We used VW values from global model studies, whereas VW data from a national model for Pakistan might be a better choice for future studies on VW trade and footprint. The results for fruits and vegetables should be read with caution because the grouping and reporting for the two sectors are significantly broader than all the other commodities in this study. Future studies should include more detailed analysis for both the groups of commodities, although greywater footprint is also a pertinent topic covered in many studies on VW trade. However, because the environmental side of the virtual water trade (covering greywater) is beyond the scope of this study, future studies should include grey virtual water as well. Due to the unavailability of data on the cost of production for the studied commodities at the national level in Pakistan, we had to use production value for estimating the value of virtual water. Although this is not the ideal measure to account for differences in cost/benefit of various agricultural commodities, the measure still provides the closest proxy for evaluating the economic value of virtual water in agricultural production. Our study did not include the social costs that are often associated with blue water use in exportable commodities. Adding these costs is expected to further support our assertion regarding the inclusion of virtual water trade into domestic water policies. The analysis of water use in agriculture within the country is also an essential topic for prioritizing water use in the country. However, it is out of the scope of this study and should be covered in the future work

5. Conclusions

The quantification of virtual water trade provides an essential perspective on sustainable water use practices. Using Pakistan as a case study, this paper assessed the trade and savings/losses of blue and green virtual water through agricultural commodities, over the period 1990–2016 and in 2030. The results of our study show that in most of the studied commodities, blue VW is the major component in the total water use. Pakistan's export of VW increased more rapidly than the import of VW over 1990–2016. On average, the net VW import (import minus export) was positive but small. Pakistan has been a net exporter of blue VW, mostly through rice export to Asian and African countries. In terms of green VW, Pakistan has been a net importer, mainly through the import of palm oil from Indonesia and Malaysia.

In terms of domestic savings, Pakistan's trade in the agricultural commodities has been saving green VW for the country. However, Pakistan has been losing increasingly higher volumes of blue VW through its agricultural trade over the study period. Putting this into perspective, the blue VW loss was equivalent to about 7% of the total agricultural water withdrawal in the country in 2011. Pakistan's trade in the agricultural commodities has also contributed to positive savings of blue and green virtual water at the global level.

In the future (2030), both Pakistan's domestic savings of green and losses of blue virtual water will increase by more than 200%. The global savings will increase by more than three times for green VW and more than 120% for blue VW. Our results also suggest that Pakistan has been exporting more expensive (with high opportunity cost) blue VW through its agricultural trade to the rest of the world and can thus benefit from improvements in water use efficiency (in the export-oriented crops) and adjustment in its export portfolio of agricultural commodities by promoting the export of commodities with higher value and lower water use intensity.

As discussed in detail, two major shortcomings should be addressed in future research. First, time-series data from the national model(s) should be used in place of the global estimates for VWC. This will enhance the reliability of the results to produce more reliable policy suggestions. Second, time-series data for grey VW for the agricultural commodities are needed to analyze the environmental effects of trade in agricultural commodities, which were not taken into account in this study.

Although numerous studies on VW trade have been published, the studies mainly concerned those countries which are either net-importers and water-stressed or net-exporters and water-abundant. Given that water availability is more crucial for the water-stressed net-exporting countries, the trade in VW for such countries becomes more critical. The analysis of Pakistan's trade in VW through agricultural commodities presented in this study can further promote future work in water-stressed countries.

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Conflicts of Interest: The authors declare no conflict of interest.

Appendix A

Appendix A.1 Analysis of Pakistan's Agricultural Trade

Despite being an agricultural economy, Pakistan has not only been exporting some agricultural commodities, but it has also been importing significant quantities of some other agricultural commodities. A country's dependence (or independence) on foreign-produced commodities can be gauged by the self-sufficiency ratio ($SSR = \text{Production} / (\text{Production} + \text{Net import})$) based on data from Reference [39]). Pakistan's average SSR over the period 1990–2013 is shown in Figure A1.

We can observe two extremes in the SSR for Pakistan, that is, on the one hand, Pakistan has been producing almost double the amount of rice it needed for domestic consumption (SSR = 187%), implying that Pakistan exported 47% of its domestically produced rice to other countries over this period. On the other hand, Pakistan's SSR in palm oil (used as edible oil) and tea—the two largest traditional food imports of Pakistan—has been almost zero, indicating that Pakistan has been entirely dependent on other countries for its domestic needs of palm oil and tea. The less than 100% SSR values of other cereals (84%), oilseed crops (89%), wheat (96%) and cotton (96%) show that Pakistan has been importing some amounts of these commodities over the years. The rest of the commodities show relatively high (close to or more than 100%) SSR over the period.

In value terms, Pakistan's exports have been dominated by rice, which—with an average yearly export of 1645 million US\$—accounted for over 64% of the total export value of these commodities during 2003–2016 (Figure A2, yellow columns). Fruits (251 million US\$), cotton (148 million US\$), vegetables (135 million US\$) and sugar (108 million US\$) have been other major commodities recording sizable export for Pakistan during this period. The five commodities mentioned above were responsible for about 90% share in the total export value of the studied commodities.

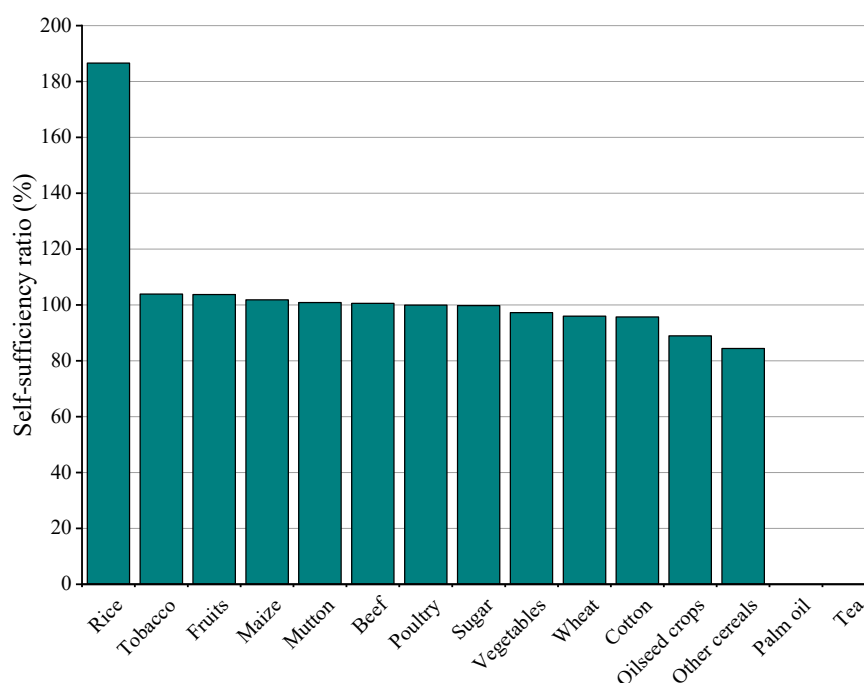


Figure A1. Average self-sufficiency ratios (SSR) of agricultural commodities for Pakistan, 1990–2013. Source: Authors' calculations based on data from Reference [39].

In terms of import value, palm oil takes the lead with an average value of 1434 million US\$ (about 37% share) among these agricultural commodities during 2003–2016. Cotton (627 million US\$), oilseed crops (544 million US\$), vegetables (438 million US\$) and tea (293 million US\$) also have significant shares in the total import value of the agricultural commodities by Pakistan during the same period. Notice that cotton, vegetables and sugar have substantial shares in both total import and total export values suggesting that over the years the production of these crops in Pakistan have experienced significant ups and downs such that during some years Pakistan exported these crops while it imported the same crops during other years.

Additionally, some quality requirements have also impacted the changing trade situation of some crops, especially in the case of cotton, where Pakistan had to import high-quality cotton from other countries to produce exportable textile goods. It is also noteworthy that although Pakistan's domestic tea production is negligible (there is some domestic production; however, this is close to zero as

compared to the total net-import) (Figure A1), the value share of tea import in total imports of the agricultural commodities has been around 8% (Figure A2).

Our future projections under business as usual (BAU) scenarios show that Pakistan will continue to export vast quantities of rice to other countries by 2030, such that its rice exports will increase by 3.3 times from the 2016 level. The exports of sugar and cattle will also increase considerably in percentage terms. However, the corresponding absolute changes will be quite small, bearing little effect on VW exports from Pakistan. At the same time, the exports of some agricultural commodities will be reduced. Notably, both cotton and fruits have relatively high exports in 2016, while their respective exports will drop by 86% and 48% by 2030. In terms of export partners, China will gain increased importance as the export destination, especially for the export of rice, fruits, vegetables and livestock products.

Pakistan's imports of palm oil, tea and cotton will increase considerably by 192%, 31% and 363% during 2016–2030. Palm oil and tea are the most significant traditional agricultural imports by Pakistan. However, our projections show that under the BAU scenario, Pakistan will turn from a net exporter of cotton to a net importer during the coming decade. In 2030, Pakistan's import sources will remain almost the same as they were in 2016.

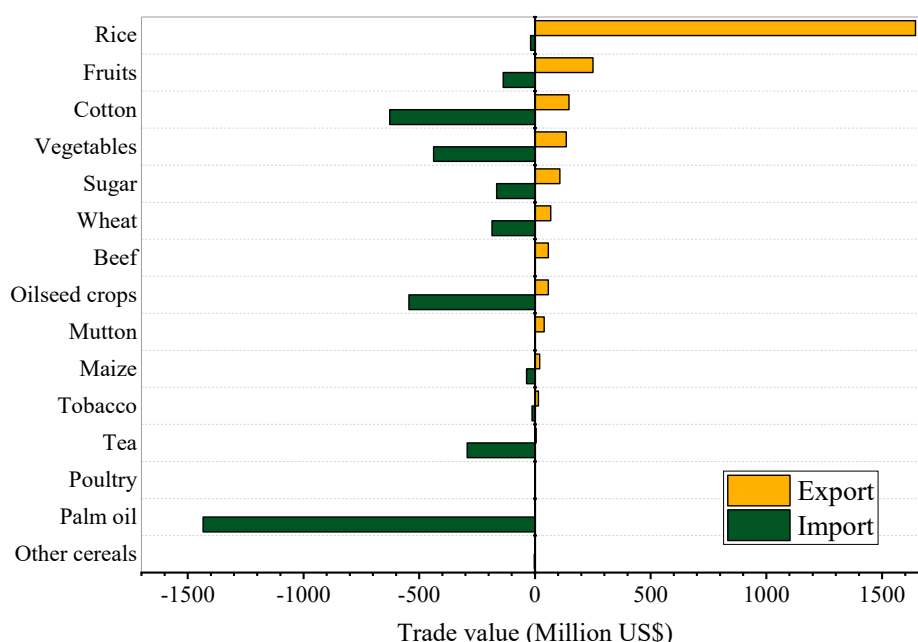


Figure A2. Average trade value of agricultural commodities, 2003–2016. Source: Authors' calculations based on data from Reference [40].

Appendix A.2 Water Resources and Use in Pakistan and its Major Trade Partners

Pakistan's water resources are scarcer than most of its major export partners. At 1711 m³/capita (By 2014, Pakistan had already become a water-stressed country with water availability 1306 m³/capita.), Pakistan is almost at the edge of entering the water scarcity threshold of 1500–1700 m³/capita in 2000 [62,71] (Table A1). Apart from Kenya, Saudi Arabia and UAE, Pakistan has much lower per capita renewable water resources than the countries it has negative net virtual water imports of blue VW. Among these three countries, Kenya is almost entirely rainfed, while Saudi Arabia and UAE have desert climates with small agriculture sectors. The per capita renewable water resources in Indonesia and Malaysia, the major import partners of Pakistan in terms of virtual water (most of which is green VW), are around 8 and 20 times that of Pakistan's.

The water use intensity in a country is reflected by the ratio of freshwater withdrawal to total renewable water resources. Again, Pakistan's ratio of 70%, which is much larger than the water

criticality threshold suggested by Reference [72], is also higher than most of its major trade partners. The ratio of irrigated area to total crop area in Pakistan is higher than most of its major trading partners, with minimal coverage in Indonesia and Malaysia.

Water stress is indicated by the ratio of total annual freshwater withdrawals to hydrological availability. Pfister (2009) [57] uses the concept of water stress to define water stress index (WSI), which indicates the portion of withdrawals of blue water that deprives other users of freshwater, ranging from zero to one (zero being no stress). We can see from the last column of Table 1A that, except the two desert regions, that is, Saudi Arabia and UAE, Pakistan's WSI is greater than all its trading partners. The higher WSI further indicates that Pakistan is exporting its scarce blue virtual water to relatively water abundant regions of the world.

List of fruits: Almonds shelled, Apples, Apricots, Apricots dry, Avocados, Bananas, Cake copra, Cashew nuts shelled, Cherries, Chestnut, Coconuts, Coconuts desiccated, Copra, Currants, Dates, Figs, Figs dried, Fruit cooked homogenized preparations, Fruit dried nes, Fruit fresh nes, Fruit prepared nes, Fruit tropical fresh nes, Grapefruit (inc. pomelos), Grapes, Hazelnuts shelled, Juice citrus concentrated, Juice citrus single strength, Juice fruit nes, Juice grape, Juice grapefruit, Juice grapefruit concentrated, Juice orange concentrated, Juice orange single strength, Juice pineapple, Juice pineapple concentrated, Kiwi fruit, Lemons and limes, Mangoes, Guavas, Nuts, nes, Nuts prepared (exc. groundnuts), Olives, Olives preserved, Oranges, Papayas, Peaches and nectarines, Pears, Persimmons, Pineapples, Pineapples canned, Pistachios, Plantains, Plums, Plums dried (prunes), Raisins, Strawberries, Tangerines mandarins, satsumas, Walnuts shelled, Walnuts with shell [39].

List of vegetables: Artichokes, Asparagus, Beans dry, Beans green, Broad beans (horse beans dry), Cabbages and other brassicas, Carrots and turnips, Cauliflowers and broccoli, Chickpeas, Chilies and peppers dry, Chilies and peppers green, Cucumbers and gherkins, Eggplants (aubergines), Garlic, Ginger, Juice tomato, Leeks other alliaceous vegetables, Lentils, Lettuce and chicory, Melons other (inc. cantaloupes), Mushrooms and truffles, Mushrooms canned, Onions dry, Onions shallots green, Peas dry, Peas green, Pepper (piper spp.), Potatoes, Potatoes frozen, Pumpkins squash and gourds, Spinach, Sweet potatoes, Tomatoes peeled, Vegetables in vinegar, Vegetables dehydrated, Vegetables fresh nes, Vegetables fresh or dried products nes, Vegetables frozen, Vegetables homogenized preparations, Vegetables preserved nes, Vegetable preserved frozen, Vegetables temporarily preserved, Watermelons [39].

Table A1. Water resources and use in Pakistan and its major trade partners, 2000 ¹.

Country	Total Renewable Water Resources (billion m ³ /year)	Total Water Withdrawal (billion m ³ /year)	Per Capita Renewable Water Resources (m ³ /capita/ year)	Per Capita Water Withdrawal (m ³ /capita/ year)	Freshwater Withdrawal as % of Total Renewable Water Resources (%)	Ratio of Irrigated Area to Total Crop Area (%)	Water Stress Index ²
Pakistan	246.8	172.6	1711	1196	69.94	55.89	0.971
Major export partners							
Afghanistan	65.33	20.28	3040	943.8	31.04	41.38	0.966
China	2840	549.8	2161	418.4	19.36	42.83	0.478
Iran	137	89.7	2024	1325	65.47	44.73	0.912
Kenya	30.7	2.32	824.1	62.28	7.557	1.899	0.021
Mozambique	217.1	0.8842	11220	45.7	0.4073	2.513	0.197
Saudi Arabia	2.4	23.67	92.01	907.5	943.3	44.08	0.995
UAE	0.15	2.904	44.2	855.6	1556	97.42	0.998
USA	3069	559.3	10639	1939	15.43	15.33	0.499
Major import partners							
Indonesia	2019	113.3	9288	521.2	5.612	13.69	0.043
Malaysia	580	9.305	23769	381.3	1.604	5.101	0.180

Source: ¹ This is the latest year for which all the data is available for these countries. ² is from Reference [57] and the rest of the information is from Reference [39].

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