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RESEARCH ARTICLE

Water footprint and virtual water trade of apples: Insights from India

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Abstract

India is a prominent producer and exporter of apples globally. However, apple cultivation requires significant water resources, and the water footprint associated with apple production and trade in India has not been thoroughly quantified. This study quantified the water footprint associated with apple production in India from 2000 to 2023, as well as the virtual water trade between 2018 and 2023. State-wise data on Indian apple production was collected and analyzed to assess the domestic water footprint, while trade data was compiled to estimate the virtual water flow associated with apple imports and exports. The results showed that the water footprint of Indian apple production averaged 2-430 million cubic meters (Mm^3) annually. This substantial footprint was primarily composed of green water (69.9%), along with blue water (23.9%) and grey water (6.2%). In terms of virtual water trade, India was a net importer with 27.8 Mm^3 of virtual water embodied in apple imports from major exporters such as Turkey, Iran and Italy. This analysis underscores the considerable water footprint of Indian apple production and the nation's significant net inflow of virtual water resources through the apple trade. Additionally, the study highlights the importance of considering virtual water flow in agricultural trade policies to achieve sustainable and equitable water resource management.

Keywords

assessing; water footprint; virtual water; apple trade; India

Introduction

Apples are among the most widely cultivated and economically significant deciduous fruit crops worldwide. Originating from the mountainous regions of Central Asia, apples have been domesticated and cultivated across Europe, Asia and the Americas for thousands of years (1). In 2022, global apple production reached approximately 95 million metric tons (MMT), with China leading at 49% of global production, followed by Turkey (5%), Poland (4%), Italy (4%) and India (FAO).

India ranked as the fifth largest apple producer globally, with a production of 2.35 MMT in 2022-23. Apple cultivation in India is predominantly concentrated in the North-Western Himalayan states of Jammu and Kashmir, Himachal Pradesh and Uttarakhand, which together accounted for around 92% of the country's total apple production during 2022-23 (IndiaStat). Climate change is significantly impacting apple cultivation in these regions. Apples, once predominantly cultivated at elevations of 1200-1500 meters, are now being grown at higher altitudes, reaching up to 3500 meters, as farmers adapt to rising temperatures. Although India is a major apple producer, it also engages in international apple trade to meet domestic demand and export surplus. India's apple production is seasonal and concentrated in the Himalayan regions, leading to periodic supply limitations that struggle to keep pace with the growing consumer demand. Imports play a crucial role in stabilizing apple prices during periods of shortage and bridging supply gaps during the off-season. Major countries of apple imports for India include Turkey, Iran, Italy, Chile, New Zealand, Poland and South Africa. Conversely, India primarily exports apples to neighbouring countries such as Bangladesh, Bhutan, and Nepal (2).

International trade in apples results in substantial "virtual water" flow across national borders, carrying embedded freshwater resources used in the production of the traded commodity. The concept of "virtual water" refers to the freshwater consumed to produce a product, which is then virtually transferred from the producing region when the product is traded (3). This concept is particularly crucial in regions facing water scarcity, where importing water-intensive crops like apples can reduce pressure on domestic water resources.

Quantifying the virtual water flow is essential to understand the pressure on freshwater resources resulting from global agricultural trade. It also helps to secure food production in areas with limited domestic water availability. The "water footprint" serves as a measure of freshwater use associated with producing a specific commodity. It includes green water (rainfall stored in soil moisture), blue water (surface and groundwater sources), and grey water (freshwater required to assimilate pollutants) (4). In apple cultivation, green water supports growth in rain-fed orchards, reducing the need for irrigation. Blue water is used to irrigate apple orchards during dry spells or in water-scarce regions and grey water accounts for the freshwater required to dilute pollutants from fertilizers and pesticides used in orchards, preventing contamination of water bodies. Studies on the water footprint of crop production are essential for identifying opportunities to improve water use efficiency in agriculture.

When combined with trade data, the water footprint allows for the quantification of virtual water flow through the virtual water trade (VWT) - the import and export of virtual water resources embedded in traded products like agricultural commodities (5). The concept of virtual water refers to the volume of water embedded in the production of goods, which is indirectly exchanged between countries through trade. This framework provides insights into the environmental impact of agricultural trade, serving as a critical tool for assessing sustainable water management and informing agricultural policies. By revealing the hidden water flow associated with imports and exports, VWT highlights how trade can influence regional water availability (6). Nations with high water footprints for water-intensive crops can conserve domestic water resources by relying more on imports, while those with lower footprints can strategically leverage export opportunities. There is considerable potential to enhance crop water productivity, relocate agricultural production to regions with lower water scarcity, and reconsider our dietary habits. These strategies could contribute to more sustainable water management and resource allocation, thereby addressing the challenges posed by water scarcity and climate change (7). By quantifying the water footprints and VWT of this high-value fruit crop, this research provides insights to guide more sustainable production practices, facilitate interstate allocation of water resources and formulate suitable trade policies for India.

Materials and Methods

Data Collection

Data on the total area, production, and productivity of apples in India and its major Indian states were sourced from INDIASTAT for the period 2000-2023. This data is used to assess the water footprint of apple production. Additionally, data on average annual precipitation in major apple-growing states and monthly reference evapotranspiration rates for these states from 2000 to 2023 were collected from the Indian Meteorological Department (IMD) website. Data on apple trade, including import and export quantities of apples, as well as the top import and export destinations during the years 2018 to 2023, was obtained from the Ministry of Commerce, Government of India (GOI) website.

Crop Water Requirement (CWR)

Crop water requirement refers to the amount of water necessary for crops to support their growth and development throughout their life cycle. It can be calculated by adjusting the potential evapotranspiration (E_{T0}) based on crop-specific factors like the crop coefficient (K_c), which accounts for the difference between potential and actual crop water use at various growth stages (8).

$$E_T = K_c \times E_{To} \quad \text{..........(1)}$$

where, E_T - The crop water requirement (mm), K_c - The crop coefficient and E_{To} - The reference evapotranspiration (mm).

Virtual Water Content (VWC)

Virtual water content is defined as the amount of water embedded in each unit mass of a product. VWCs are commonly assessed in three categories like green, blue, and grey to highlight the impacts of precipitation, surface and groundwater usage and the application of chemical fertilizers (9).

$$VWC = VWC\ green + VWC\ blue + VWC\ grey \quad \text{..........(2)}$$

where, VWC - The total virtual water content (m^3/ton), VWC green - The green virtual water content (m^3/ton), VWC blue - The blue virtual water content (m^3/ton), and VWC grey - The grey virtual water content (m^3/ton).

The green VWC of the crop is estimated by dividing the effective rainfall by the crop yield. The blue VWC of the crop is calculated as the ratio of the volume of irrigation water used to the crop yield (10), and the grey VWCS is calculated by dividing the nitrogen application rate by the difference between the maximum acceptable nitrogen concentration and the natural nitrogen concentration in the receiving body.

$$\text{VWC green} = (\text{Effective Rainfall}) / (\text{crop yield}) \quad \ldots\ldots\ldots\ldots(3)$$

$$\text{VWC blue} = (\text{Volume of irrigation water used}) / (\text{crop yield}) \quad \ldots\ldots\ldots\ldots(4)$$

$$\text{VWC grey} = L / (cmax - cnat) * 1/C \quad \ldots\ldots\ldots\ldots(5)$$

$$L = \propto * APL \quad \ldots\ldots\ldots\ldots(6)$$

where, α - The leaching fraction, APL - Nitrogen fertilizer application rate (kg/time), cmax - The maximum acceptable concentration of nitrogen fertilizer in the receiving water body (kg/m^3), cnat - The natural concentration of nitrogen fertilizer in the receiving water body (kg/m^3) and C - Production amount in tonnes.

Water Footprint of Crop Production

The water footprint of crop production represents the total volume of water used, both directly and indirectly, during the cultivation process. Crop water footprints can differ significantly both between and within regions (11). To determine the total water footprint of a specific product within a defined geographical region, one can multiply its VWC by the total mass of production (4).

$$WF_c = VWC \times C \quad \ldots\ldots\ldots\ldots(7)$$

where, WF_c - the total water footprint of crop production (m^3/year), C - production amount in tonnes, and VWC - the virtual water content (m^3/ ton).

Virtual Water Trade (VWT)

Virtual water trade refers to international trade of water that is embedded within agricultural products, encompassing both the import and export of this virtual water. It is influenced by various factors, including population, GDP, and geographical distance (12).

$$VWI_{C,N} = VWC_{C,N} * I_{C,N} \quad \ldots\ldots\ldots\ldots(8)$$

$$VWE_{C,N} = VWC_{C,N} * E_{C,N} \quad \ldots\ldots\ldots\ldots(9)$$

where, $VWC_{C,N}$ - The virtual water content of apple C and country N, $VWI_{C,N}$ - The virtual water import of apple C from country N, $VWE_{C,N}$ - The virtual water export of apple C from country N, $I_{C,N}$ - The import quantity of apple C from country N and $E_{C,N}$ - The Export quantity of apple C from country N.

Virtual Water Trade Balance (VWB)

The virtual water balance is determined by subtracting the total export of virtual water from the total import. When the quantity of Virtual Water Imports (VWI) surpasses that of Virtual Water Exports (VWE), the Net Virtual Water Balance (VWB) is positive, signifying an excess of imported virtual water. On the other hand, if the volume of VWI is lower than that of VWE, the VWB becomes negative, signifying a net export of virtual water.

$$TVWI_C = \sum VWI_{C,N} \quad \ldots\ldots\ldots\ldots(10)$$

$$TVWE_C = \sum VWE_{C,N} \quad \ldots\ldots\ldots\ldots(11)$$

$$TVWB_C = TVWI_C - TVWE_C \quad \ldots\ldots\ldots\ldots(12)$$

where, $TVWI_C$ - The total virtual water import of apple C from all the countries, $TVWE_C$ - The total virtual water export of apple C for all the countries and $TVWB_C$ - The Total Virtual Water Balance for apple C for all the countries.

Results and Discussion

Crop Water Requirement

The Crop Water Requirement (CWR) for apples varied significantly across different Indian states. In Uttarakhand, the CWR was the highest among the major apple-growing regions, reaching 9126.17 m^3/ha. This was notable, because Uttarakhand also had the lowest apple yield compared to other states. On the other hand, Jammu and Kashmir, which had the highest apple yield, recorded the lowest CWR at 8336.79 m^3/ha and the CWR for Himachal Pradesh was calculated to be 8355.42 m^3/ha. This variation in CWR highlighted the differing water requirements and agro-climatic conditions in these regions (Table 1). Uttarakhand experienced higher temperatures and greater evapotranspiration rates compared to Jammu & Kashmir and Himachal Pradesh, leading to increased water demand for apple cultivation to maintain adequate soil moisture. A study conducted by Ahmad (13) estimated the CWR of apples in major apple-growing districts of the Kashmir Valley, finding the highest in the Srinagar district (9530 m^3/ha) and the lowest in the Baramulla district (8460 m^3/ha).

Table 1. Average crop water requirement of apples in major apple-growing states from 2000 to 2023.

Indian States	CWR (m^3/ha)
Jammu and Kashmir	8336.79
Himachal Pradesh	8355.42
Uttarakhand	9126.17
Mean	8606.13

Virtual Water Content of Apples in the Major Producing States

The study revealed notable differences in water consumption among key apple-producing states, reflecting the varying climatic conditions and irrigation practices. Uttarakhand exhibited the highest water consumption, with green and blue VWC recorded at 2272.27 m^3/ton and 724.05 m^3/ton, respectively. Conventional irrigation techniques, such as flood and basin irrigation are still prevalent in the state leading to inefficient water use and substantial losses through evaporation and seepage, contributing to its high VWC. Himachal Pradesh followed closely, with green and blue VWC of 1229.52 m^3/ton and 439.45 m^3/ton, respectively, indicating a relatively lower dependency on irrigation compared to Uttarakhand, likely due to more favourable precipitation patterns during the growing season. Jammu and Kashmir, another major apple-producing state, demonstrated the lowest water consumption among the three, with green and blue VWC of 580.81 m^3/ton and 196.88 m^3/ton, respectively. The lower figures in Jammu and Kashmir reflected the region's efficient use of natural precipitation and less intensive irrigation practices (Fig. 1). These findings highlighted the critical role of water management in apple production across different states, with implications for sustainability and resource conservation in the agriculture sector.

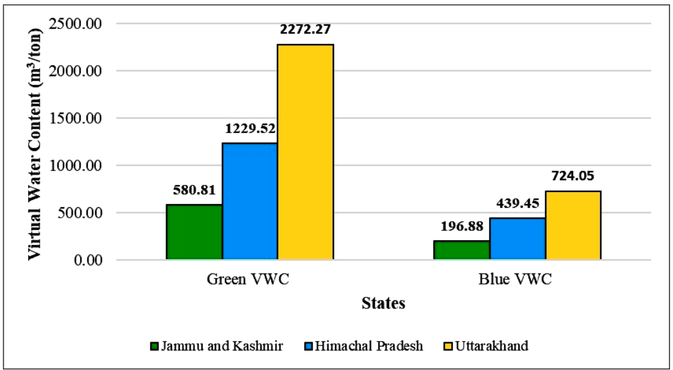

Fig. 1. Virtual water contents of apple production in major apple-growing states.

Water Footprint of Indian Apple Production

The water footprint of apple production in India was dominated by green water, with blue and grey water also playing significant roles, as noted by Kampman (14). This dominance of green water indicated that the majority of water utilized in apple cultivation was derived from natural precipitation, underscoring the importance of favourable climatic conditions in sustaining apple orchards. Among the major apple-growing states, Jammu and Kashmir exhibited the highest water footprint for apple cultivation, totalling 1,160 Mm^3. This large footprint could be attributed to the extensive area under apple cultivation in the state and the reliance on natural precipitation, which, while plentiful, necessitated careful management to avoid overuse. Himachal Pradesh followed, with a water footprint of 870 Mm^3, reflecting the state's considerable apple production and the significant role of green water in sustaining its orchards. Despite its relatively smaller production scale, Uttarakhand recorded a water footprint of 250 Mm^3, as detailed in Table 2. The lower footprint in Uttarakhand, compared to the other states, could be indicative of both a smaller cultivated area and possibly more efficient water use practices, although the state's higher blue water consumption suggested a greater reliance on irrigation during periods of insufficient rainfall. In all these states, the green water footprint constituted the majority of the total water footprint, highlighting the critical dependence of apple cultivation on natural precipitation. This reliance on green water emphasized the vulnerability of apple production to changes in precipitation patterns, particularly in the context of climate change, which could alter precipitation regimes and affect water availability. The water footprints associated with apple production in the Indian states of Himachal Pradesh, Jammu and Kashmir and Uttarakhand vary considerably when compared to those of major international apple-growing regions. Many leading apple-producing countries exhibit lower VWC. For example, Turkey's VWC is about 261.38 m^3/ton, consisting of 174.48 m^3/ton of green water and 58.16 m^3/ton of blue water. Iran demonstrates a significantly higher total VWC of 946.36 m^3/ton, predominantly due to its high blue water component of 675.97 m^3/ton. Conversely, Italy and New Zealand report lower water footprints, with Italy's VWC at 219.07 m^3/ton and New Zealand's at 231.80 m^3/ton (Author's calculations). These findings underscore that while Indian states heavily depend on both green and blue water for apple cultivation, numerous international regions have adopted more efficient water management practices, leading to reduced water footprints in apple production. Consequently, the findings stressed the need for enhanced water management strategies that not only optimized the use of green water but also ensured the sustainable use of blue and grey water to support long-term agricultural productivity.

Table 2. Water footprints (WF) for major apple-growing states in India from 2000 to 2023

States	WF green	WF blue	WF total
Jammu and Kashmir	870 (75.0)	290 (25.0)	1160 (100.0)
Himachal Pradesh	640 (73.5)	230 (26.5)	870 (100.0)
Uttarakhand	190 (76.0)	60 (24.0)	250 (100.0)

The overall blue and green VWC of apples in India were determined by averaging the values from the major apple-producing states, while the grey VWC was calculated based on the average nitrogen fertilizer consumption for apples across the country. The average VWC for apple production in India was found to be 1885.52 m^3/ton, which included 1360.87 m^3/ton of green water, 453.46 m^3/ton of blue water and 71.19 m^3/ton of grey water. A study by Kokila (15) estimated the average VWC of apples in India to be 3632.8 m^3/ton and the crop water requirement to be 6,696.1 m^3/ha for the year 2007-08. The total water footprint for Indian apple production was 2430 Mm^3 predominated by green water at 1700 Mm^3 (69.9%), blue water at 580 Mm^3 (23.9%), and grey water at 150 Mm^3 (6.2%) as provided in Table 3.

Virtual Water Trade of Apples

The study provided significant insights into the import and export dynamics of apples, emphasizing the importance of international trade in meeting India's domestic apple demand. It focused on the top seven countries exporting apples to India, which collectively accounted for approximately 90% of India's total apple imports (Ministry of Com-

Table 3. Total water footprint and virtual water contents of apples in India from 2000 to 2023

	Total water footprint (Mm^3)	Share of total water footprint (%)	Average Virtual Water Content (m^3/ton)
Green	1700	69.9	1360.87
Blue	580	23.9	453.46
Grey	150	6.2	71.19
Total	2430	100	1885.52

merce, GOI). The analysis included the calculation of VWC of apples from these major exporting countries, providing a clear estimation of the virtual water import associated with apple imports into India.

Iran emerged as the largest source of virtual water imports, contributing 37.1% of the total virtual water imports with a substantial volume of 17 Mm^3/year. This significant contribution highlighted Iran's critical role in satisfying India's growing apple consumption, reflecting the extensive agricultural water consumption in Iran's apple production, which was indirectly transferred to India through the importation of apples. The dominance of Iranian apples in the Indian market underscored the strong trade ties between the two countries in the agricultural sector, particularly in horticulture. Following Iran, Turkey was identified as the second-largest contributor, with virtual water imports amounting to 8.2 Mm^3, representing 17.9% of the total virtual water imports. This figure reflected Turkey's position as a key player in the global apple trade and its strategic importance in India's import portfolio. Chile, another major exporter, contributed 7.1 Mm^3, accounting for 15.5% of India's virtual water imports. Chile's significant share underscores its role as a reliable supplier of high-quality apples to India, supported by its efficient agricultural practices and favourable climatic conditions that enable year-round production. The sustainability of apple production in Turkey and Chile generally surpasses that of India, primarily due to their efficient irrigation methods and favourable climatic conditions. While Turkey and Chile utilize advanced technologies and practices to maintain lower VWC, India faces challenges such as reliance on traditional irrigation techniques and vulnerability to climate change, which contribute to higher water footprints in apple cultivation. The remaining countries among the top seven exporters also played vital roles in India's apple import landscape, contributing to the overall virtual water imports. These findings, detailed in Table 4, illustrate the interconnectedness of global trade and water resources, where the importation of apples into India not only satisfied domestic demand but also represented the transfer of substantial volumes of water embedded in these agricultural products.

A study by Chapagain (16) emphasized the critical role of irrigation in agricultural production, especially in arid and semi-arid regions where natural rainfall was insufficient to meet crop water requirements. This focus on irrigation aligned with the high blue water import from Iran observed in the study, where a significant portion of apple production relied heavily on supplemental irrigation. Their findings highlight the necessity of irrigation infrastructure and water management practices in sustaining agricultural productivity in such water-scarce regions, a point reflected in the data for Iran.

Table 4. Virtual water imports from major apple exporting countries to India from 2018 to 2023

Country	Virtual Water Imports (Mm^3/year)	Share of total Virtual Water Imports (%)
Turkey	8.2	17.9
Iran	17.0	37.1
Italy	5.3	11.6
Chile	7.1	15.5
New Zealand	4.1	8.9
Poland	2.4	5.3
South Africa	1.7	3.7
Total	45.8	100

The study's analysis revealed that the overall virtual water imports associated with apple imports into India amounted to 45.8 Mm^3/year. This substantial volume underscored the extent to which India relied on external water resources, embedded in imported agricultural products, to meet its domestic demand for apples. The breakdown of this virtual water import by type-green, blue, and grey water-provided further insight into the water resource implications of international trade. The share of green, blue and grey water in the total virtual water imports is depicted in Fig. 2, illustrating the diverse sources of water embedded in the apples imported into India.

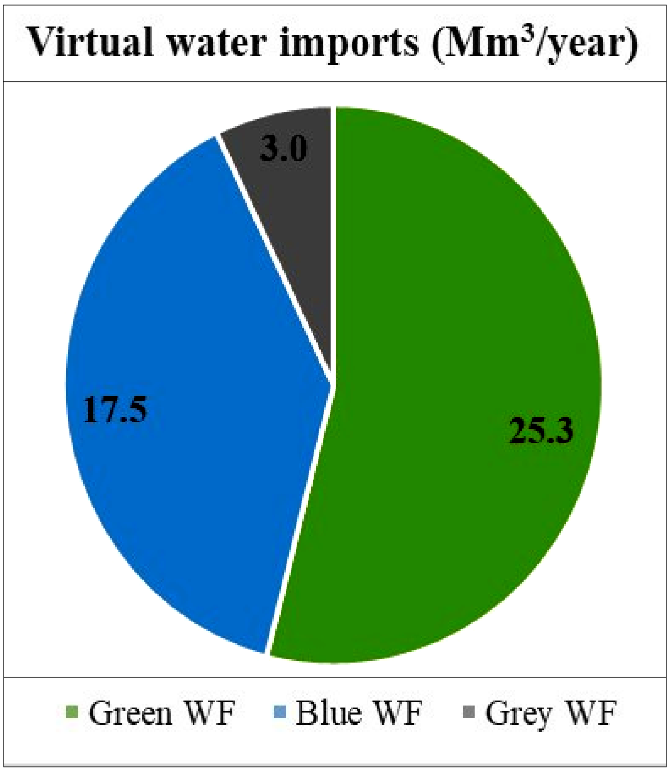

Fig. 2. Green, blue and grey virtual water imports into India.

Regarding export, the study examined the top three countries importing apples from India, which together accounted for approximately 90% of India's total apple exports. This focus on major export destinations provided crucial insights into the flow of virtual water from India to its neighbouring countries, highlighting the agricultural trade relationships that influence regional water resource dynamics.

Bangladesh emerged as the leading importer of Indian apples, receiving the highest amount of virtual water exports of 9.3 Mm^3/year, representing 51.7% of India's total virtual water exports. This substantial share emphasized Bangladesh's reliance on Indian apples to satisfy its domestic demand, thereby indirectly depending on the water resources used in India for apple cultivation. Nepal, as the second-largest importer, receives 8.1 Mm^3/year of virtual water, which accounted for 45% of the total virtual water exports from India. The significant volume of virtual water flowing to Nepal reflected the strong trade ties between the two nations, with Nepal being a key market for Indian apples. This virtual water export also indicated the dependence of Nepal's apple consumption on the agricultural practices and water management strategies employed in India. Bhutan, although a smaller market, was the third major importer, receiving 0.6 Mm^3/year of virtual water, which constituted 3.3% of India's total virtual water exports. While the volume is relatively modest compared to Bangladesh and Nepal, the VWT with Bhutan still plays a role in the regional distribution of water resources through agricultural exports. In total, India exported 18 Mm^3/year of virtual water through its apple trade, reflecting the significant water resources embedded in the apples shipped to neighbouring countries. The composition of this virtual water export, in terms of green, blue and grey water, is illustrated in Fig. 3.

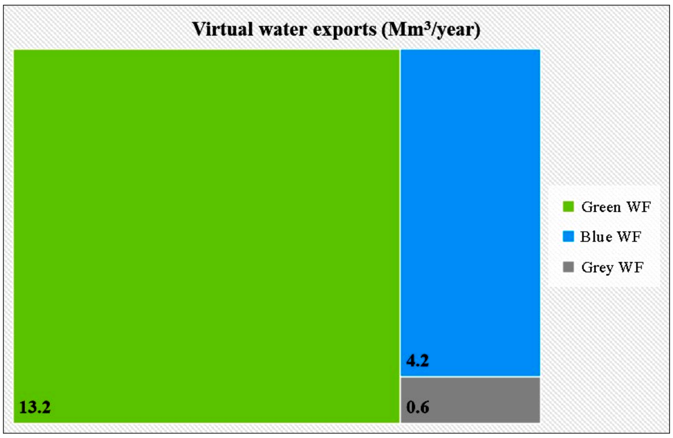

Fig. 3. Green, blue and grey virtual water exports from India.

The total virtual water balance for apples in India was calculated by subtracting the total virtual water exports from the total virtual water imports. This calculation provided a clear picture of India's net VWT position in the apple sector. The resulting VWT balance was 27.8 Mm^3/year (Fig. 4), indicating that India was a net virtual water importer in this sector, as noted by Shivaswamy (17). This positive virtual water balance signified that India imported more water, in the form of virtual water embedded in apples, than it exported through its apple trade. The implications of this net import position are significant for India's overall water resource management. The excess virtual water imported through apples could potentially be reallocated or offset by reducing the pressure on domestic water resources used in the production of other agricultural commodities.

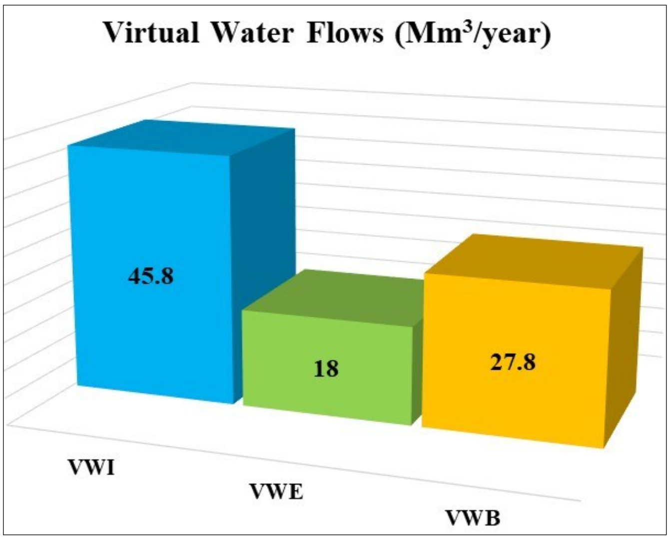

Fig. 4. Virtual water flow through apple trade in India from 2018 to 2023.

Conclusion

This study provides important insights into the water footprint of apple production in India and its impact on virtual water trade. The findings emphasize the considerable dependence on rainwater (green water) for apple cultivation, while also revealing significant use of irrigation water and the necessity for water treatment to mitigate pollution. The high proportion of green water usage indicates a potential to improve rainwater harvesting methods and soil moisture retention practices. This could potentially reduce the reliance on irrigation and conserve blue water resources, which are often under greater stress. The substantial blue water footprint highlights the necessity for more efficient irrigation systems and water-saving technologies in apple orchards. To enhance rainwater harvesting and irrigation efficiency in apple production, strategic policy measures, such as providing subsidies for rainwater systems and promoting efficient irrigation technologies, are essential. Additionally, integrating community engagement and education on sustainable practices can significantly improve water management and contribute to long-term food security and resource sustainability. Although the grey water footprint is smaller, it underscores the need to address water pollution from agricultural runoff. Implementing policies that encourage sustainable fertilizer and pesticide use, along with enhanced wastewater treatment, could help reduce this impact. The analysis of VWT reveals that India, as a net virtual water importer of apples, strategically alleviates pressure on its domestic water resources by importing a water-intensive crop rather than producing it locally. This is especially crucial in regions suffering from severe water scarcity, as it minimizes the need for extensive irrigation, thereby preserving vital blue water resources such as freshwater stored in lakes, rivers and aquifers. By importing apples, India not only reduces the risk of depleting water in already stressed areas but also bolsters food security by maintaining a reliable supply of the fruit without further burdening its limited water reserves. Furthermore, this approach enables India to allocate its water resources more effectively, focusing on crops that are essential for domestic consumption and agricultural sustainability, while also responding to the challenges of climate change and variable water availability. This balance between virtual water imports and local production underscores the importance of coordinated water and agricultural policies in ensuring long-term water and food security.

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Authors' contributions

All the authors participated in the design of the study and performed the analysis. All authors read and approved the final manuscript.

Compliance with ethical standards

Conflict of interest: Authors do not have any conflict of interests to declare.

Ethical issues: None

AI Declaration

During the preparation of this work the authors used QuillBot in order to improve language and readability, with caution. After using this tool, the authors reviewed and edited the content as needed and take full responsibility for the content of the publication.

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