Prabandhan Darpan - Journal of Management Studies, *Volume II (Issue I: January - April, 2026): Pages 14-25* *ISSN:3107-5983 (Online)*
Published on: May 29, 2026.



Prabandhan Darpan - Journal of Management Studies

Contents available at: *https://www.swamivivekanandauniversity.ac.in/jms/*

Evaluating Virtual Water Trade in India: Trends and Sustainability Implications (2016–2022)

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Abstract

Virtual water trade refers to the implicit transfer of water resources embedded in agricultural commodities through international trade. In a water-stressed country like India, the export of water-intensive crops raises critical sustainability concerns. This study examines India's virtual water exports and imports during the period 2016–2022. Using secondary data from DGCIS, APEDA, FAO, and recent scholarly literature, virtual water flows are quantified and analysed through descriptive statistics, correlation, and regression techniques. The findings indicate that India emerged as a net exporter of virtual water after 2017, with rice contributing the largest share of total exports. While agricultural exports contribute positively to economic growth, they intensify pressure on groundwater resources. Statistical results reveal a weak relationship between exports and imports, indicating a structural imbalance in trade dynamics. The study highlights the need to integrate virtual water accounting into agricultural trade policy and proposes a virtual water taxation framework to ensure sustainable resource management.

Keywords: *Virtual Water Trade, Agricultural Exports, Water Footprint, Sustainability, India*

1. Introduction

Water is a fundamental resource for agricultural production, economic development, and human survival. Globally, agriculture accounts for approximately 70 per cent of total freshwater withdrawals, making it the largest consumer of water resources (FAO, 2021). In the context of increasing population pressure, climate variability, and resource scarcity, efficient water management has become a critical policy concern, particularly in developing economies. One of the most significant conceptual developments in this area is the notion of *virtual water*, which refers to the volume of water embedded in the production of goods and services that are traded across regions or countries. The concept was first introduced by Allan (1993) to explain how water-scarce countries can achieve food security by importing water-intensive commodities rather than producing them domestically. This idea was later expanded by Hoekstra and Hung (2002), who developed a systematic framework for quantifying international virtual water flows. Through global trade, countries effectively exchange not only goods but also the water resources used in their production processes, making virtual water trade an important mechanism for redistributing global water resources.

From a theoretical perspective, virtual water trade is closely linked to international trade theories such as comparative advantage and the Heckscher–Ohlin model. These frameworks suggest that countries should specialise in producing and exporting goods that utilise their relatively abundant resources efficiently. In the context of water, this implies that water-abundant countries should export water-intensive products, while water-scarce countries should rely more on imports. However, empirical evidence often deviates from these theoretical expectations, particularly in

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developing economies where policy interventions, institutional factors, and market distortions significantly influence production and trade patterns. India presents a particularly important case for analysing virtual water trade dynamics. The country supports nearly 17 per cent of the global population but possesses only about 4 per cent of the world's freshwater resources (World Bank, 2022). Over the past few decades, rapid population growth, urbanisation, and agricultural intensification have significantly increased pressure on water resources. Groundwater, which serves as a major source of irrigation, has been extensively exploited in several regions, leading to declining water tables and long-term sustainability concerns (Central Ground Water Board, 2021).

Despite these constraints, India has emerged as one of the largest exporters of agricultural commodities, particularly rice, which is highly water-intensive. The expansion of agricultural exports has been supported by government procurement policies, minimum support price mechanisms, and strong global demand. While such exports contribute positively to economic growth and foreign exchange earnings, they also imply a substantial outflow of embedded water resources. This raises an important question regarding the sustainability of India's current agricultural trade patterns from a water resource perspective. Existing literature has examined various aspects of virtual water trade, including measurement of water footprints, global trade flows, and sustainability implications. Studies such as Mekonnen and Hoekstra (2011) provide comprehensive estimates of water footprints across countries, while Kumar and Jain (2007) highlight India's role as a net exporter of virtual water. More recent studies have emphasised the environmental implications of exporting water-intensive crops, particularly in regions experiencing groundwater depletion (Uma et al., 2021; Nishad & Kumar, 2022). However, much of the existing research focuses on earlier periods or relies primarily on descriptive approaches without integrating statistical testing of trade relationships.

In recent years, global trade patterns and domestic agricultural policies have undergone significant changes, particularly in the post-2016 period. Despite this, there remains limited empirical evidence examining the dynamics of virtual water exports and imports using updated data. Moreover, the relationship between exports and imports of virtual water has not been adequately analysed using statistical techniques such as correlation and regression. Understanding this relationship is crucial for assessing whether trade patterns are balanced or driven predominantly by export expansion. In addition to economic and environmental considerations, the issue of virtual water trade is increasingly being examined within the broader framework of sustainable development. The United Nations Sustainable Development Goals (SDGs), particularly SDG 6 (Clean Water and Sanitation) and SDG 12 (Responsible Consumption and Production), emphasise the need for efficient resource use and sustainable management of natural resources. In this context, the export of water-intensive agricultural commodities from water-stressed regions raises concerns regarding intergenerational equity and long-term ecological balance.

Climate change further intensifies these challenges by altering precipitation patterns, increasing the frequency of extreme weather events, and affecting water availability across regions. In India, the monsoon-dependent agricultural system is particularly vulnerable to such changes. Variability in rainfall not only impacts crop yields but also increases reliance on groundwater irrigation, thereby accelerating resource depletion. Consequently, the interaction between climate change and virtual water trade adds a layer of complexity to policy formulation. Furthermore, recent policy debates in India have begun to acknowledge the importance of integrating environmental considerations into agricultural trade decisions. While traditional policy frameworks have prioritised food security and farmer welfare, there is growing recognition of the need to incorporate sustainability metrics such as water footprint and resource efficiency into decision-making processes. This shift highlights the relevance of virtual water accounting as a tool for designing more balanced and sustainable trade policies.

Against this backdrop, the present study seeks to evaluate India's virtual water trade dynamics during the period 2016–2022. Specifically, the study aims to: (i) analyse trends in virtual water exports and imports; (ii) examine the statistical relationship between these flows; and (iii) assess the sustainability implications of crop-wise virtual water exports, particularly in the case of water-intensive commodities such as rice. By integrating water accounting with

statistical analysis, the study contributes to a more comprehensive understanding of the economic and environmental dimensions of agricultural trade in India.

2. Methodology

The present study adopts a quantitative and descriptive research design to examine the dynamics of virtual water trade in India during the period 2016–2022. The analysis focuses on estimating the volume of water embedded in agricultural exports and imports and evaluating the statistical relationship between these flows. The relevance of the study lies in assessing the sustainability implications of trade patterns in a water-constrained economy.

The study relies entirely on secondary data obtained from credible and publicly available sources, including the Directorate General of Commercial Intelligence and Statistics (DGCIS), the Agricultural and Processed Food Products Export Development Authority (APEDA), and reports published by the Food and Agriculture Organisation (FAO). These sources provide detailed information on trade volumes of major agricultural commodities, which form the basis for estimating virtual water flows.

The measurement of virtual water trade is grounded in the concept of the water footprint, which quantifies the amount of water used in the production of a commodity. In this study, virtual water content coefficients, expressed in cubic meters per ton (m^3/ton), are used to convert trade volumes into water equivalents. These coefficients are derived from established literature, particularly the work of Mekonnen and Hoekstra (2011), which provides standardised estimates of water use across crops.

Virtual water exports and imports are calculated by multiplying the physical trade volume of each commodity (in tons) by its corresponding virtual water content. This relationship is expressed as:

Virtual Water Flow = Trade Volume × Virtual Water Content

where trade volume represents the quantity of a commodity exported or imported, and virtual water content represents the amount of water required to produce one unit of that commodity. The resulting values are aggregated to estimate total virtual water exports and imports for each year and are reported in billion cubic meters (bcm) for analytical clarity.

To evaluate the balance of trade in water terms, net virtual water export is computed as the difference between total exports and total imports. A positive value indicates that the country is a net exporter of virtual water, while a negative value indicates net import dependence.

In addition to descriptive analysis, the study employs statistical techniques to examine the relationship between virtual water exports and imports. Pearson correlation analysis is used to measure the strength and direction of association between the two variables. Furthermore, a simple linear regression model is specified to assess whether variations in virtual water imports significantly explain changes in exports over time. The model is expressed as:

$VWE_t = \alpha + \beta VWI_t + \varepsilon_t$

where VWE_t represents virtual water exports in year t, VWI_t represents virtual water imports in year t, α is the intercept term, β is the regression coefficient, and ε_t is the error term.

The following hypotheses guide the study:

H_0: There is no significant relationship between virtual water exports and imports.

H_1: There is a significant relationship between virtual water exports and imports.

While the methodology adopted in this study provides a structured approach to estimating virtual water flows, certain limitations must be acknowledged. First, the use of standardised virtual water content coefficients may not fully capture regional variations in water use efficiency. In reality, water requirements for crop production vary significantly across states due to differences in climate, soil conditions, irrigation practices, and technological adoption. However, due to data constraints, the study relies on average coefficients, which may lead to minor estimation biases.

Second, the analysis is based on aggregate national-level data, which limits the ability to capture intra-regional disparities in water use and trade patterns. Given that water scarcity in India is highly localised, a more disaggregated analysis at the state or basin level could provide deeper insights into the sustainability implications of virtual water trade.

Third, the statistical analysis is constrained by the limited number of observations available for the study period. With only a small time series dataset, the application of advanced econometric techniques is restricted. As a result, the correlation and regression analysis presented in this study should be interpreted as indicative rather than conclusive.

Despite these limitations, the methodology offers a useful framework for integrating water accounting with trade analysis. By combining quantitative estimation with statistical tools, the study provides a comprehensive overview of virtual water trade dynamics and lays the groundwork for more detailed future research.

Given the limited number of observations for the study period, the statistical results are interpreted cautiously, focusing on indicative trends rather than establishing strong causal relationships. The methodology thus integrates water accounting with basic econometric analysis to provide a comprehensive assessment of the dynamics of virtual water trade in India.

3. Water Trade

Water trade refers to the exchange of water resources between regions, sectors, or countries through physical transfers or market-based mechanisms. It is increasingly recognized as an important strategy for managing water scarcity, improving resource allocation, and supporting economic development. Water trade can occur directly, such as through the transfer of water rights or bulk water supplies, or indirectly through the exchange of goods and services that require water for production. In regions experiencing water stress, water markets allow users to buy and sell water entitlements, enabling water to move from lower-value to higher-value uses. This can enhance efficiency, support agricultural productivity, and promote sustainable resource management. However, water trade also raises concerns regarding equity, environmental sustainability, and access to water for vulnerable communities. Excessive commercialization may disadvantage small farmers and marginalized populations if regulatory frameworks are weak. Therefore, effective governance, transparent pricing mechanisms, and environmental safeguards are essential to ensure that water trade contributes to sustainable development. As climate change, population growth, and urbanization intensify pressure on freshwater resources, policymakers and researchers increasingly view water trade as a tool for balancing competing demands while promoting economic resilience and water security at local, national, and international levels.

The concept of virtual water refers to the amount of water embedded in the production of goods and services that are traded between regions or countries. Introduced by Tony Allan in the 1990s, the concept highlights how water-scarce nations can effectively import water by purchasing water-intensive products such as food, textiles, and industrial goods rather than producing them domestically. Recent virtual water trends indicate a substantial increase in global trade flows of water-intensive commodities, driven by globalization, changing consumption patterns, and growing international supply chains. Agricultural products account for the largest share of virtual water trade, particularly cereals, meat, dairy products, cotton, and processed foods. Emerging economies have become major participants in virtual water networks, while water-scarce countries increasingly rely on imports to reduce pressure on domestic water resources. Advances in water footprint assessment and sustainability reporting have further enhanced understanding of virtual water flows. However, concerns remain regarding the environmental consequences of exporting water-intensive products from regions already experiencing water stress. Current research emphasizes the need for integrating virtual water considerations into trade, agricultural, and water management policies. As climate change and water scarcity become more pronounced, virtual water analysis is expected to play a crucial role in promoting sustainable resource use, food security, and global water governance.

3.1 Virtual Water Trade Trends in India

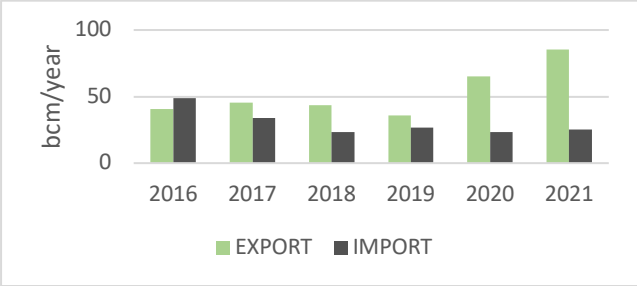
The analysis of virtual water trade in India during the period 2016–2022 reveals a clear and sustained expansion in the volume of embedded water exported through agricultural commodities. Virtual water exports increased significantly from approximately 40.586 billion cubic meters (bcm) in 2016–17 to 85.424 bcm in 2021–22, representing more than a twofold increase over a relatively short period. In contrast, virtual water imports remained comparatively moderate and exhibited limited fluctuation over the same period. This divergence between export and import trends indicates a structural shift toward export-oriented virtual water flows in India's agricultural trade.

Table 1: Virtual Water Exports and Imports (2016–2022)

Year	Exports (bcm)	Imports (bcm)
2016–17	40.586	48.827
2017–18	45.498	33.918
2018–19	43.29	23.57
2019–20	35.746	26.742
2020–21	64.977	23.282
2021–22	85.424	25.146

(Source: Author's calculation based on DGCIS & APEDA data)

Figure 1: Trend of Virtual Water Exports and Imports (2016–2022)



(Source: Author's calculation based on DGCIS & APEDA data)

As shown in Table 1 and Figure 1, virtual water exports from India exhibit a clear upward trend over the study period, while imports remain relatively stable. The widening gap between exports and imports indicates a structural shift toward export-oriented virtual water flows. This pattern suggests that India is increasingly relying on its domestic water resources to support agricultural exports, raising concerns about long-term sustainability in the context of water scarcity.

The increasing trajectory of virtual water exports can be attributed to several interrelated factors. First, the expansion of agricultural production, particularly of export-oriented crops such as rice, has played a central role. Government support mechanisms, including minimum support prices (MSP) and procurement policies, have incentivised the cultivation of specific crops irrespective of their water intensity. Consequently, production decisions are often shaped more by assured pricing structures than by considerations of resource efficiency.

Second, rising global demand for staple commodities, especially rice, has reinforced India's position in international markets. The country's competitive pricing and large-scale production capacity have enabled it to emerge as a leading exporter. This has resulted in a corresponding increase in the volume of water embedded in exported goods, effectively transferring domestic water resources to importing countries in virtual form.

The trend analysis further indicates that India has consistently maintained a surplus in virtual water trade throughout the study period. The gap between exports and imports widened substantially after 2017, indicating a transition toward a strong net-export position. While this reflects deeper integration into global agricultural markets, it also raises concerns regarding the sustainability of such trade practices in a water-constrained environment. These findings are consistent

with recent studies highlighting the environmental implications of export-driven water use in agriculture (Dalin et al., 2020; Rosa et al., 2020).

From a resource management perspective, the persistent export surplus implies that a significant proportion of domestically available freshwater is being allocated to produce goods destined for international markets. This is particularly critical in the context of declining groundwater levels in major agricultural regions. The heavy reliance on irrigation for crop production, especially in states characterised by intensive farming systems, further amplifies pressure on already stressed water resources.

Another important dimension of the trend analysis is the concentration of virtual water exports in a limited number of crops. Rice dominates the export basket in water terms, accounting for a substantial share of total virtual water outflows. Given the inherently water-intensive nature of paddy cultivation, this concentration intensifies the environmental implications of export expansion. The limited diversification toward less water-intensive crops suggests that current trade patterns are not aligned with principles of sustainable resource utilisation.

At the same time, the relatively stable trend in virtual water imports indicates that India has not significantly increased its reliance on external sources for water-intensive commodities. In theory, strategic imports could serve as a mechanism for conserving domestic water resources by shifting production burdens to water-abundant regions. However, the observed pattern suggests that import strategies have not been effectively leveraged as a tool for water resource management.

India's export expansion during the study period is also closely linked to regional patterns of agricultural production. States such as Punjab and Haryana, which form the core of India's Green Revolution belt, have significantly contributed to rice exports despite experiencing severe groundwater depletion. The widespread adoption of tube-well irrigation, supported by subsidised electricity, has enabled the continuous extraction of groundwater for paddy cultivation. However, this has resulted in a steady decline in water tables, raising serious concerns about long-term sustainability (Central Ground Water Board, 2021).

Furthermore, the sharp increase in exports observed after 2020 can be partly attributed to global supply chain disruptions during the COVID-19 pandemic. As several countries faced production constraints, India capitalised on its surplus production capacity to expand exports, particularly of staple commodities. While this contributed to short-term economic gains, it also accelerated the outflow of virtual water, intensifying pressure on domestic water resources.

Climate variability further complicates this dynamic. Changes in monsoon patterns, increased frequency of droughts, and rising temperatures have affected water availability across regions. In such a context, the continued expansion of water-intensive exports may increase vulnerability to climate shocks. This underscores the need to align export strategies with long-term resource sustainability considerations.The continued expansion of water-intensive exports without corresponding adjustments in cropping patterns or trade strategies may increase vulnerability to water scarcity and climate variability. These trends provide a crucial foundation for further statistical analysis of export–import dynamics

3.2 Statistical Analysis of Export-Import Dynamics

To further examine the structure of India's virtual water trade, statistical analysis was conducted to evaluate the relationship between virtual water exports and imports during the study period. While trend analysis provides a descriptive understanding of trade patterns, statistical tools such as correlation and regression offer insights into whether these patterns exhibit systematic relationships.

Table 2: Correlation and Regression Results

Variable	Value
Correlation (r)	-0.407
R^2	0.166
Significance	Not Significant

(*Source:* computed using SPSS)

As presented in Table 2, the correlation between virtual water exports and imports is weak and negative, indicating the absence of a strong linear relationship between the two variables. The low R^2 value further suggests that variations in imports do not significantly explain export behaviour. This implies that export growth is largely driven by domestic production policies and external demand rather than balanced trade adjustments.

The Pearson correlation coefficient between virtual water exports and imports was estimated at –0.407, indicating a weak negative association between the two variables. This suggests that increases in export volumes are not accompanied by corresponding increases in imports. The negative sign further implies that periods of higher exports tend to coincide with relatively lower import levels, although the strength of this relationship remains limited.

The weak negative correlation observed between exports and imports also reflects the structural nature of India's agricultural trade. Unlike market-driven systems where trade flows adjust dynamically to resource constraints, India's export patterns are significantly influenced by policy interventions. As a result, export decisions are often decoupled from considerations of resource scarcity.

In particular, minimum support prices and procurement policies create strong incentives for farmers to produce specific crops, thereby driving export volumes independently of import trends. Similar patterns of weak trade balancing mechanisms have been observed in developing economies, where policy-driven exports dominate trade structures (Mukherji et al., 2021).

It is also important to consider the limitations posed by the small sample size. With only a limited number of observations, the statistical analysis may not capture more complex dynamic relationships between exports and imports. Future research using longer time series data could provide deeper insights into these interactions. Nevertheless, the present findings offer a useful indication of the underlying structural patterns in India's virtual water trade.

From an economic standpoint, this weak and inverse relationship reflects the absence of a balancing mechanism in virtual water trade. In an ideal scenario, a resource-constrained country might offset the export of water-intensive goods by increasing imports of similar commodities, thereby maintaining a degree of resource equilibrium. However, the observed correlation indicates that such compensatory adjustments are largely absent in India's trade pattern.

To further investigate this relationship, a simple linear regression model was estimated, with virtual water exports as the dependent variable and imports as the explanatory variable. The results indicate that the coefficient of determination (R^2) is 0.166, implying that only 16.6 per cent of the variation in exports can be explained by changes in imports. This relatively low explanatory power suggests that import dynamics play a minimal role in influencing export behaviour.

Moreover, the estimated regression coefficient was found to be statistically insignificant at conventional levels, reinforcing the conclusion that there is no strong predictive relationship between the two variables. In other words, fluctuations in virtual water imports do not significantly influence export patterns over time.

These findings have important implications for understanding the underlying drivers of virtual water trade in India. The absence of a significant relationship between exports and imports suggests that export expansion is largely independent of import behaviour. Instead, it is primarily driven by domestic agricultural policies, production incentives, and global market demand. For instance, policy instruments such as minimum support prices and procurement systems may encourage the cultivation and export of specific crops without accounting for their water intensity.

Additionally, international demand conditions and price competitiveness play a crucial role in shaping export performance. India's strong presence in global rice markets, for example, has sustained export growth irrespective of import trends. This reinforces the argument that virtual water trade patterns are influenced more by economic and policy factors than by considerations of resource balance.

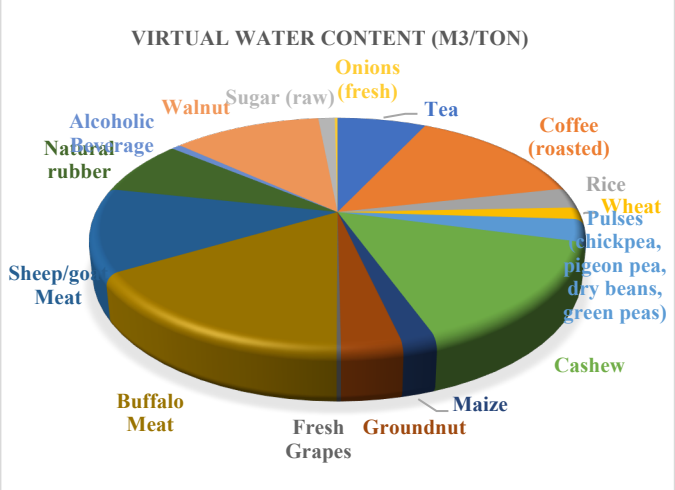
From a sustainability perspective, the lack of a statistically significant relationship between exports and imports raises concerns about long-term resource implications. Since export growth is not offset by increased imports of water-intensive goods, the net effect is a continuous outflow of embedded water resources. Over time, this may exacerbate water scarcity, particularly in regions already experiencing groundwater depletion.

It is important to acknowledge that the interpretation of statistical results is constrained by the limited number of observations in the study period. With only a small time series dataset, the analysis captures broad tendencies rather than definitive causal relationships. Nevertheless, the consistency of results across both correlation and regression analysis provides reasonable evidence of the structural independence of export growth.

3.3 Crop-wise Virtual Water and Sustainability Implications

An important dimension of virtual water trade analysis lies in examining the contribution of individual crops to total embedded water flows. The composition of exports plays a critical role in determining the sustainability of trade patterns, as different crops vary significantly in their water requirements. In the case of India, the analysis reveals a high concentration of virtual water exports in a limited number of agricultural commodities, with rice emerging as the dominant contributor.

Figure 2: Crop-wise Share in Virtual Water Exports



(Author's calculation)

Figure 2 highlights the dominance of rice in India's virtual water exports, accounting for the largest share of total embedded water outflows. This concentration reflects the high-water intensity of rice cultivation and indicates limited diversification in the export basket. Such dependence on a single water-intensive crop amplifies pressure on freshwater resources and raises concerns regarding efficient resource utilisation.

Rice accounts for a substantial proportion of India's total virtual water exports throughout the study period. This dominance is particularly significant because rice cultivation is inherently water-intensive, especially under irrigated conditions. Paddy cultivation requires a continuous water supply during the growing season, often relying heavily on groundwater extraction in regions where canal irrigation is insufficient. Consequently, the expansion of rice exports directly translates into increased withdrawal of freshwater resources. Recent studies have also linked the expansion of virtual water exports to increasing groundwater stress in India (Nishad & Kumar, 2022).

From the perspective of resource efficiency, this concentration raises important concerns. According to the principle of comparative advantage, countries should specialise in goods that utilise their abundant resources. However, India's continued emphasis on exporting water-intensive commodities appears inconsistent with its status as a water-stressed country. This suggests that production and trade decisions are influenced by institutional and policy factors rather than resource endowments.

One of the key drivers behind this pattern is the system of minimum support prices and assured procurement. These policies provide income stability to farmers and encourage the cultivation of specific crops, often without accounting for their environmental cost. While such interventions are essential for food security and rural livelihoods, they may inadvertently promote resource-intensive agricultural practices, leading to inefficient allocation of water resources.

The water footprint of rice production further illustrates the magnitude of the issue. On average, the production of one kilogram of rice requires between 3000 and 5000 litres of water, depending on climatic conditions and irrigation practices. This makes rice one of the most water-intensive crops in the agricultural sector. Consequently, the large-scale export of rice implies a substantial transfer of freshwater resources in virtual form.

In regions such as northwestern India, where groundwater is the primary source of irrigation, this has led to unsustainable extraction levels. The imbalance between withdrawal and recharge has resulted in declining aquifers, threatening the long-term viability of agricultural production systems. This is particularly concerning given the increasing uncertainty associated with climate change and rainfall variability.

In contrast, alternative crops such as millets and pulses require significantly lower water inputs and are better suited to semi-arid conditions. Promoting such crops could reduce pressure on water resources while enhancing climate resilience. However, the transition toward less water-intensive crops requires supportive policy measures, including market incentives, price support, and awareness among farmers.

The lack of diversification in India's export basket also limits the adaptive capacity of the agricultural sector. A more diversified cropping system would not only reduce environmental stress but also enhance economic stability by reducing dependence on a single commodity. Therefore, addressing the concentration of virtual water exports is essential for achieving both environmental sustainability and economic resilience.

The sustainability implications of this pattern are particularly evident in regions characterised by high dependence on groundwater for irrigation. Intensive groundwater extraction to support water-intensive crops has led to declining water tables in several agricultural states. This trend is further aggravated by low recharge rates and increasing climatic variability. As groundwater levels decline, the cost of extraction rises, increasing financial stress on farmers and reducing long-term agricultural viability.

In addition to environmental concerns, the concentration of exports in a few crops reduces the resilience of the agricultural system. Limited diversification makes the system more vulnerable to market fluctuations and climatic shocks. For example, changes in international demand or adverse weather conditions could significantly affect both export earnings and production stability. Promoting diversification toward less water-intensive crops could enhance resilience while reducing pressure on water resources.

Another critical aspect is the role of imports in managing water stress. In principle, importing water-intensive commodities allows countries to conserve domestic water resources by shifting production to regions with greater water availability. However, the analysis indicates that India's import patterns have not evolved significantly to support such a strategy. The relatively stable level of virtual water imports suggests that trade policy has not been actively utilised as a tool for optimising water use.

From a policy perspective, these findings highlight the need for a more integrated approach to agricultural trade and water resource management. Aligning cropping patterns with regional water availability, promoting water-efficient irrigation technologies, and incorporating environmental considerations into export policy decisions are essential steps toward sustainability.

Furthermore, integrating virtual water accounting into policy frameworks can provide a more comprehensive basis for decision-making. Evaluating exports not only in terms of economic value but also in terms of resource use can help policymakers design strategies that balance growth with sustainability. This is particularly important in the context of increasing water scarcity and climate change, which are likely to intensify resource constraints in the future.

Overall, the crop-wise analysis underscores the need to reassess current agricultural trade patterns in India. While export growth has generated economic benefits, it has also intensified pressure on limited water resources. Achieving long-term sustainability will require a transition toward more resource-efficient production and trade practices supported by appropriate policy interventions.

4. Discussion

The findings of the study provide important insights into the structure and implications of virtual water trade in India. By combining trend analysis with statistical examination, the study reveals a pattern of export-driven expansion in embedded water flows, accompanied by limited adjustment in import behaviour. This section interprets these findings in the context of existing literature and theoretical frameworks.

The findings of this study are consistent with a growing body of global literature that highlights the paradoxical nature of virtual water trade. While the concept was originally proposed as a mechanism to improve global water use efficiency, empirical evidence suggests that trade patterns do not always align with resource endowments. In several cases, water-scarce countries continue to export water-intensive commodities, thereby exacerbating domestic resource stress.

4.1 The Debate

This contradiction can be better understood in the context of second-best economic theory, where market imperfections, policy distortions, and institutional constraints prevent the optimal allocation of resources. In the case of India, agricultural trade is heavily influenced by government interventions such as minimum support prices, input subsidies, and procurement policies. These interventions, while essential for ensuring food security and farmer income stability, often distort production incentives and lead to suboptimal resource use.

Moreover, the role of global value chains and international market dynamics cannot be overlooked. Developing countries like India often participate in global agricultural trade as suppliers of primary commodities, where competitiveness is driven by cost advantages rather than resource efficiency. This creates a situation where short-term economic gains from exports may outweigh long-term environmental considerations, leading to unsustainable trade patterns.

Another important dimension is the concept of "externalisation of environmental costs." Through virtual water exports, importing countries effectively benefit from the water resources of exporting nations without bearing the associated environmental costs. This raises important ethical and policy questions regarding the distribution of resource burdens in global trade. Addressing this issue may require international cooperation and the development of sustainability standards that account for embedded resource use.

The study also highlights the need to rethink the application of comparative advantage in the context of natural resource constraints. Traditional trade theories assume that factor endowments are exogenously given and efficiently utilised. However, in the presence of environmental degradation and resource depletion, these assumptions may no longer hold. Incorporating ecological constraints into trade models could provide a more realistic framework for analysing trade patterns in resource-scarce economies.

The results of the present study reinforce this argument by showing that export growth has been substantial during the post-2016 period, particularly in the case of rice. However, the findings also point to a divergence from the theoretical expectations of comparative advantage and factor endowment models. According to these frameworks, countries are expected to specialise in the production of goods that utilise their abundant resources efficiently.

In the case of water, this would imply that water-scarce countries should limit exports of water-intensive products. The continued expansion of such exports in India suggests that trade patterns are influenced by policy and institutional factors rather than purely by resource availability. The statistical analysis further strengthens this interpretation by demonstrating that there is no significant relationship between virtual water exports and imports. This indicates that export growth is not accompanied by a compensatory increase in imports of water-intensive goods. Such a pattern reflects an imbalance in virtual water trade, where the outflow of embedded water is not offset by inflows from external sources.

Similar observations have been made in studies that emphasise the role of domestic policy frameworks in shaping agricultural trade outcomes. From a sustainability perspective, the dominance of water-intensive crops in the export

basket raises concerns about long-term resource management. The findings align with existing literature that highlights the environmental implications of intensive groundwater extraction in agricultural regions. Continued reliance on irrigation-dependent crops, particularly in water-stressed areas, may exacerbate groundwater depletion and reduce resilience to climate variability. At the same time, the results underscore the importance of considering trade policy as a tool for resource management.

While traditional trade analysis focuses on economic efficiency and competitiveness, the concept of virtual water introduces an environmental dimension that cannot be ignored. Integrating water considerations into trade policy could help align economic objectives with sustainability goals. The study also highlights the role of government interventions in shaping production and export patterns. Policies such as minimum support prices and procurement systems provide incentives for the cultivation of specific crops, often without accounting for their environmental impact. While these policies are essential for ensuring food security and farmer welfare, their unintended consequences on resource use need to be carefully evaluated.

Another important implication of the findings is the need for diversification in agricultural production. Reducing dependence on a limited number of water-intensive crops can enhance both economic resilience and environmental sustainability. Encouraging the adoption of less water-intensive alternatives, along with improved irrigation practices, can help optimise resource use without compromising productivity.

Overall, the discussion suggests that India's virtual water trade reflects a complex interaction between economic incentives, policy frameworks, and environmental constraints. Addressing the challenges identified in this study will require a more integrated approach that considers both the economic and ecological dimensions of agricultural trade. Such an approach is essential for ensuring that export growth does not come at the cost of long-term water security.

4.2 Conclusion

The findings of the study highlight the need for a comprehensive policy framework that integrates water resource management with agricultural trade strategies. One of the most important policy innovations in this context is the concept of a virtual water tax on water-intensive exports.

A virtual water tax involves imposing a levy on agricultural commodities based on the volume of water embedded in their production. Crops with higher water footprints, such as rice, would attract higher tax rates compared to less water-intensive crops. This would create an economic disincentive for excessive production and export of water-intensive commodities, encouraging a shift toward more sustainable cropping patterns.

The revenue generated from such a tax could be reinvested in improving irrigation infrastructure, promoting water-efficient technologies such as drip and sprinkler systems, and supporting groundwater recharge initiatives. This would help offset the environmental cost of virtual water exports while enhancing long-term resource sustainability.

In addition to taxation, crop diversification should be promoted as a key strategy for reducing water stress. Encouraging farmers to shift from water-intensive crops to alternatives such as millets, pulses, and oilseeds can significantly reduce water consumption. This transition can be supported through targeted subsidies, improved market access, and extension services.

Another critical area of intervention is the reform of water pricing and electricity subsidies. The current system of free or highly subsidised electricity for irrigation encourages excessive groundwater extraction. Introducing rational pricing mechanisms can help promote efficient water use while reducing resource depletion.

Furthermore, trade policy should incorporate environmental considerations by integrating virtual water accounting into export decision-making processes. Evaluating trade flows in terms of both economic value and resource use can help design policies that balance growth with sustainability.

Overall, a combination of fiscal instruments, institutional reforms, and technological interventions is required to ensure that India's virtual water trade remains economically beneficial while being environmentally sustainable.

5. Conclusion

This study examined the dynamics of virtual water trade in India during the period 2016–2022 by analysing trends, statistical relationships, and crop-wise contributions. The findings indicate a consistent increase in virtual water exports, with export volumes significantly exceeding imports, resulting in a sustained surplus of embedded water outflows. Statistical analysis further reveals that export growth is not significantly associated with import behaviour, suggesting that trade expansion is largely driven by domestic production incentives and global demand rather than balanced trade adjustments. The crop-wise analysis highlights the dominance of water-intensive commodities, particularly rice, in India's export basket. This pattern raises concerns regarding the sustainability of current trade practices, especially in the context of groundwater depletion and increasing water stress in major agricultural regions. The results underscore the need to reconsider existing production and trade strategies from a resource management perspective. The study suggests that integrating water considerations into agricultural and trade policy can help align economic objectives with environmental sustainability. Promoting crop diversification, improving irrigation efficiency, and incorporating resource-based assessment frameworks into policy design may contribute to more sustainable outcomes. Future research may extend the analysis by incorporating longer time series data and regional-level variations to provide more detailed insights into virtual water trade dynamics.

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