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Towards a virtual water currency for industrial products using blockchain technology

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ABSTRACT

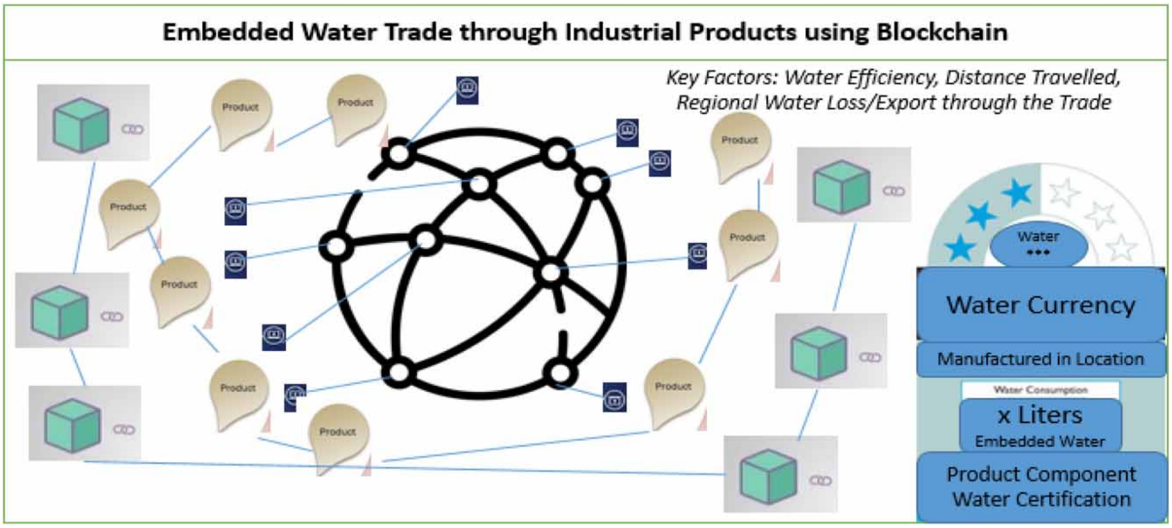
Tracking unseen water in products (Embedded Virtual Water) has generated great interest in the scientific community. This water transfers between geographies via suppliers, manufacturers, distributors, retailers and customers in multiple phases. However, the Virtual Water Trading System lacks proper accounting standards, established protocols and processes in the context of product manufacturing. Therefore, there is a need to establish a technology platform to handle the complex virtual water international trade. Such a platform should uphold transparency and create 'water consciousness' and awareness among companies and consumers. The concept of a virtual water currency and blockchain technology platform together can manage these processes. Blockchain helps in setting up secure, verifiable, scalable and traceable systems. Blockchain manages the audit and contract management processes with ease. Virtual water currency is critical to advocate sustainability. The objective of this paper is to establish the key linkages between virtual water and usage of blockchain. A systematic literature survey was conducted on 16 journal repositories (153 journal papers) of IWA Publishing to establish virtual water linkages and five journal databases (IEEE Xplore, Sciencedirect, ACM Digital Library, Springer Link and Wiley Online Library covering 5026 journal papers) for blockchain and water management linkages. This study proposes to introduce virtual water currency and set up an International Virtual Water Trading System using blockchain. The proposed platform seamlessly integrates the quality, cost and sustainability of industrial products and their sub-components.

Key words: Blockchain, Product traceability, Virtual water, Water footprint, Water management

HIGHLIGHTS

- Virtual water trading in the context of product manufacturing lacks proper accounting and sensitization. Therefore, it is important to set up a technology platform to build water consciousness and awareness among companies and consumers.
- Virtual water currency plays a profound role in building sustainability.
- Blockchain technology helps in setting up a secure, verifiable, scalable and traceable system.

GRAPHICAL ABSTRACT



INTRODUCTION

The virtual water of a product (a commodity, good or service) is defined as the volume of freshwater used to produce the product, measured at the place where the product is actually produced (Hoekstra & Chapagain, 2007; Hoekstra *et al.*, 2011). According to Velázquez *et al.* (2011), 'virtual water is defined as the amount of water used to produce and transform raw foodstuffs into food products, while the water footprint is the amount of virtual water plus the water used to deliver the product to the consumer'. This means virtual water is an embedded water in a commodity to produce, package and ship the product to the consumer. Water footprint is a total water consumption measured at the consumer or geography or location level. In this paper, we limit our scope to virtual water as we are dealing with water needed for product manufacturing and assembly process.

The concept of virtual water helps us to understand, realize and plan the water needed to produce goods and services. It helps us to protect water movement from water-stressed locations to water-rich locations. This strategy helps to alleviate water scarcity by utilizing water resources efficiently and consciously in a particular country. In this context, virtual water trade is gaining a lot of importance. However, there are no major tools and technologies to manage virtual water trade efficiently and transparently. Of late, blockchain technology is gaining popularity in the verification and traceability of multistep transactions needing verification. Blockchain is a distributed ledger technology (data ledger) shared by multiple entities operating over a distributed network. It is beyond technology. It is an innovation enabler and catalyst for the way partners work in the supply chain. Blockchain allows reliable sharing of information across parties with proper control on who can view and to what extent. It reduces the data loss risk and almost zero tolerance on non-accepted data. Blockchain traceability solution increases supply chain velocity. This is expected to be the most apt solution in the context of virtual water trade.

The objective of this paper is to study and identify key linkages between virtual water and usage of blockchain technology in the virtual water domain. This is achieved through a systematic literature survey on 16 journal repositories of IWA Publishing (the International Water Association) covering 153 journal publications with virtual water linkages and five journal databases (IEEE Xplore, Sciencedirect, ACM Digital Library, Springer Link and Wiley Online Library) covering 5026 articles for blockchain and water management linkages. The literature survey section describes the research approach and findings. The 'Research findings' section presents the proposal for setting up an International Virtual Water Trading System using blockchain technology, followed by a section on the threats to validity. The final section summarizes our contribution.

LITERATURE SURVEY

The goal of this survey is to understand the key drivers of technical, cultural and managerial factors impacting virtual water trade in a global setting. It addresses the following research question, 'What are the different motivational factors driving Virtual Water Trade in a Global Environment?' We resorted to a systematic literature survey in order to comprehend the depth of the study made in this body of knowledge. We chose IWA Publishing as a base repository for our survey. IWA Publishing is the one of the rich digital knowledge repositories in the area of water management and allied fields with an established network with water associations across the world. This repository consists of leading journals connected to the water domain. Further, we attempted to review blockchain technology application in the water domain across various journal databases.

Research process

We employed content analysis in the form of observation and analysis of existing data sets to identify the critical factors driving virtual water management in a global setting. Content analysis provides a deep systematic perspective to the research direction (Downe-Wamboldt, 1992). This particular study focuses on written text available in journal papers, books and web resources. It is a study of mute evidence of text (Hodder, 1994).

We developed a codebook with various categories classified in a staggered approach. This codebook is used for analysis, critical interpretations and deriving key factors driving virtual water currency in product trade in the context of the international market and its adoption of blockchain technology.

The Virtual Water Codebook is divided into nine categories, namely, article description (year, name of journal or conference, name of the title, volume no, doi), author key words, abstract, relevancy with Virtual Water, Location, Technology Solution, Trade/Commerce Solution, Agriculture Related/Non-Agri Product and Key Theme.

Data collection process

We adopted the key term search process to 16 journal repositories of IWA Publishing (the International Water Association), as listed in Table 1. We used the search term 'Virtual Water'. We conducted the search in July 2021. We included journal articles (excluded images) and article types (Research Article, Review Article and Editor's Choice) without any specific date range. The total number of hits was 153, as shown in Table 1.

Further, we attempted to understand blockchain adoptability in water and related areas. We used the search terms Blockchain & Water Management. We completed the search process in the same period mentioned above, July 2021. Table 2 presents the results.

We covered the following journal databases. We also used the following filter conditions for the various databases.

- IEEE Xplore Filter Criteria: Search Term-('Full Text & Metadata': Blockchain) AND ('Full Text & Metadata': Water Management). Date range: 1884–2022. Only conferences, journals and early access articles are included. Books and magazines are excluded in the search.
- Sciencedirect Filter Criteria: Search Term – blockchain for water management. Article Type: review articles, research articles, conference abstracts and case reports.

Table 1 | Database search results (virtual water).

Sr. No.#	Journal name	No. of hits
1	*AQUA*	31
2	*Blue-Green Systems*	3
3	*H_2Open Journal*	5
4	*Hydrology Research*	5
5	*Ingenieria del agua*	1
6	*Journal of Hydroinformatics*	6
7	*Journal of Water & Climate Change*	9
8	*Journal of Water & Health*	0
9	*Journal of Water, Sanitation & Hygiene for Development*	0
10	*Water Policy*	57
11	*Water Practice & Technology*	0
12	*Water Quality Research Journal*	0
13	*Water Research*	0
14	*Water Reuse*	0
15	*Water Science & Technology*	12
16	*Water Supply*	24
Total		153

- ACM Digital Library: Filter Criteria: Search Term – [All: blockchain] AND [All: water management]. Content Type: Research Articles.
- Springer Link: Filter Criteria: Search Term – 'blockchain AND water'. Content Type: Article, Conference Papers and Conference Proceedings.
- Wiley Online Library: Search Term – Blockchain for Water Management. Content Type: Journals.

Part 1: Article demographics (virtual water in IWA Publications)

We found a total of 153 articles related to virtual water across the various journal repositories of IWA Publishing. The year-wise distribution of articles is depicted in Figure 1. Out of the 153 articles, we found that 10 were duplicate. We found more than 76% of articles published during 2015–2021.

Table 2 | Database search results (Blockchain & Water Management).

Sr. No.#	Database name	No. of hits
1	IEEE Xplore	1295
2	Sciencedirect	823
3	ACM Digital Library	1732
4	Springer Link	915
5	Wiley Online Library	261
Total		5026

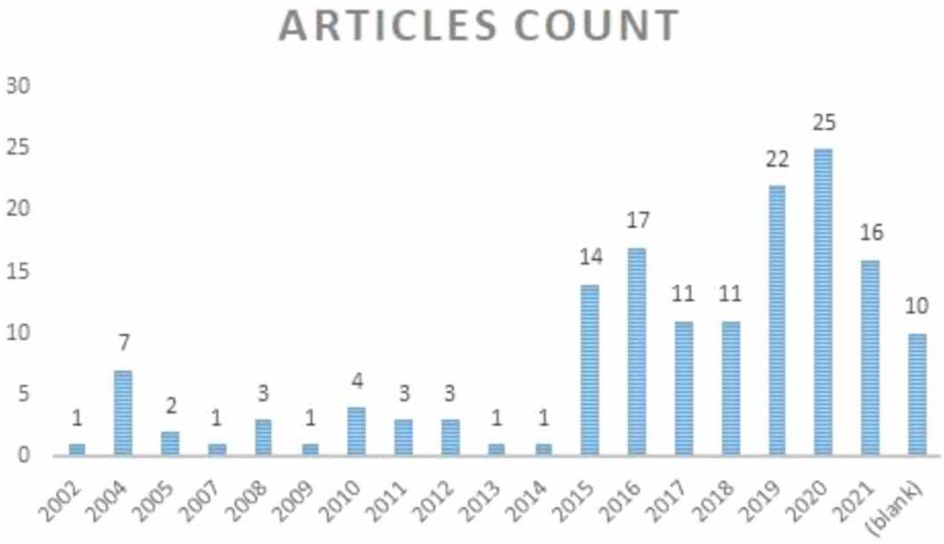


Fig. 1 | Year-wise number of articles.

We observed that only 68 out of the 153 articles had a close relationship with virtual water and water footprint management, as depicted in Figure 2.

China, with 28% of articles, had a large share of articles related to virtual water, as shown in Figure 3. We observed that 30% of the articles had no specific location linkage. The next major share was with Africa (11%), followed by Europe (9%), India (6%) and the Middle East (6%).

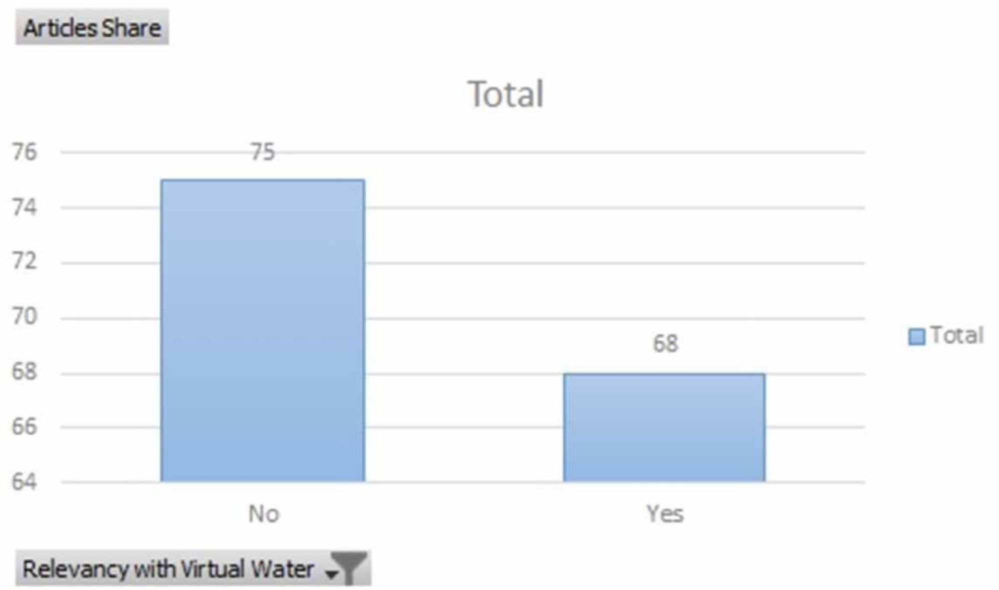


Fig. 2 | Virtual water relevancy.

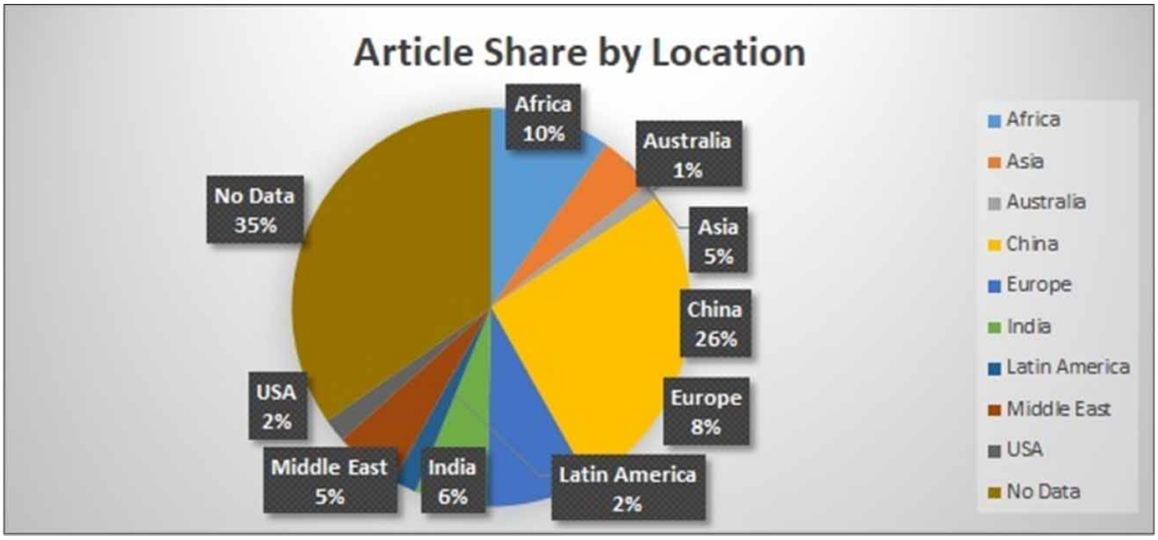


Fig. 3 | Articles shared by location.

We observed that around 20% of articles had hi-tech solutions, as depicted in Figure 4. Among them, only 9% of the articles were related to virtual water or water footprint.

We observed that around 39% of articles were related to water commerce or virtual water trading, as depicted in Figure 5.

We observed that around 43% of articles were related to virtual water in an agricultural context, as depicted in Figure 6. We found that a few articles discussed the subject of industrial trading in a virtual water context.

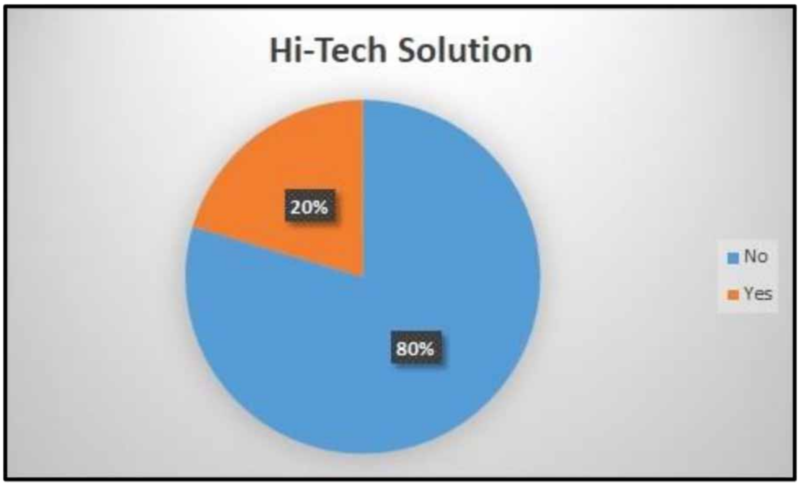


Fig. 4 | Articles with hi-tech solution/adoption.

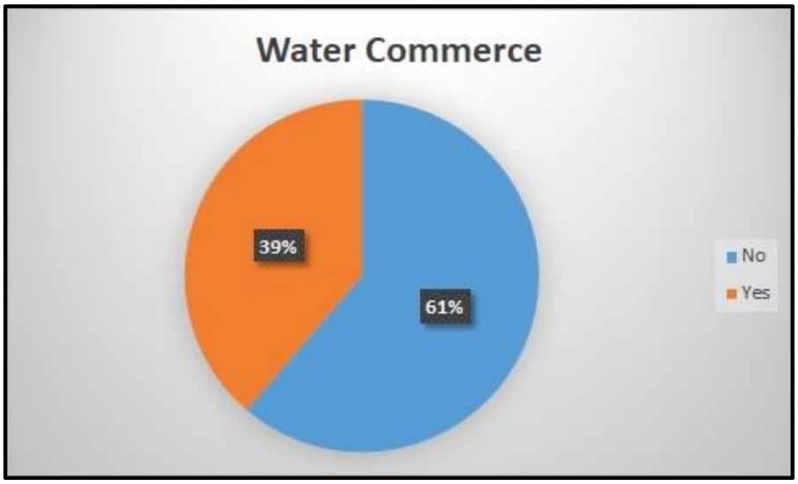


Fig. 5 | Articles with Water Commerce/Virtual Water Trading.

Part 2: Article demographics (blockchain for water management in journal databases)

We observed that IEEE Xplore published articles related to Blockchain & Water Management after the year 2015. The highest share was in 2020 with 39% of articles, followed by 29% in 2020 and 17% in 2021. This only shows the nascence of blockchain technology in the water domain (Figure 7).

Similarly, we observed that ScienceDirect published articles related to Blockchain & Water Management after the year 2016, as shown in Figure 8. We considered only review articles, research articles, conference abstracts and case reports. The year 2021 had the highest article share with 44%, with the lowest being 2022 (one article) and 2016 (two articles). The ScienceDirect year-wise pattern looks similar to that of IEEE XPlore.

We observed that the ACM Digital Library published Blockchain & Water Management–related articles after the year 2013, touching a peak in 2019, as shown in Figure 9.

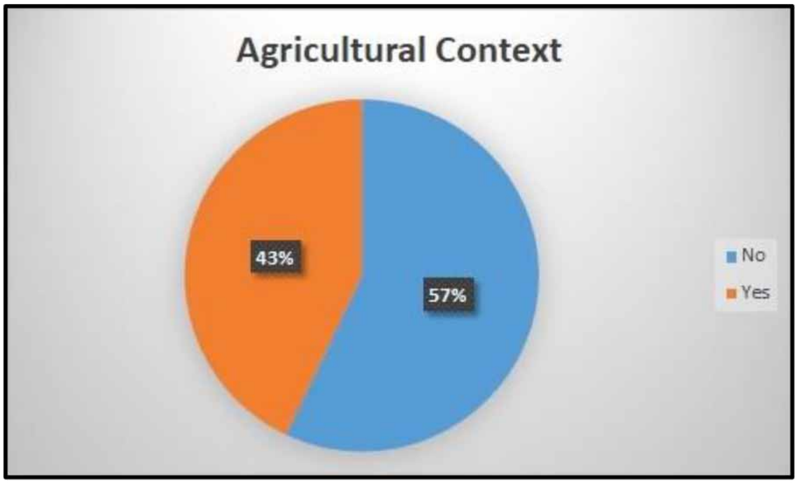


Fig. 6 | Articles with virtual water in an agricultural context.

We observed that SpringerLink published Blockchain & Water Management–related articles after the year 2016, touching a peak in 2021 (53%), as shown in Figure 10.

Similarly, Wiley Online Library reported 261 articles from 2016 to 2021. The Business and Management domain shared the highest number of articles (60).

RESEARCH FINDINGS

Part 1: Importance of virtual water trade

The International Food Policy Research Institute published an article on 'impact on food security and rural development of reallocating water from agriculture' in the year 1999. This paper presented that global trade in food (with trade in cereals) was expected to increase from 186 mt in 1993 to 349 mt in 2020 (Rosegrant & Ringler, 1999). According to the Food and Agriculture Organization of the United Nations, the world's actual cereal production value is 2710 mt and the trade value is 440.1 mt, which is closer to a 20-year-old prediction (World Cereal Inventories, 2021). These data attest to two important aspects of the trade: Prediction of the value and the volume of embedded water. This trade also highlights the water movement from water-shortage countries to water-abundant countries. Virtual water or embedded water or indirect water refers to the water consumed during the production of goods and services. Virtual water flows/trade helps us to understand how water resources in one country are consumed in another country.

The Middle East region faces severe water scarcity. A study recommends international cooperation to manage available regional water resources and its reverse depletion. It recommends virtual water trade to mitigate water depletion and build water security. Crops with high virtual water can be imported to make strategic agricultural investments in a fast-globalizing economy (Bozorg-Haddad *et al.*, 2020).

Zhang *et al.* (2018) discussed a pricing model for trading in water rights between agricultural and industrial users in China because the country lacks a formal mechanism for the transfer of credit from irrigators to the

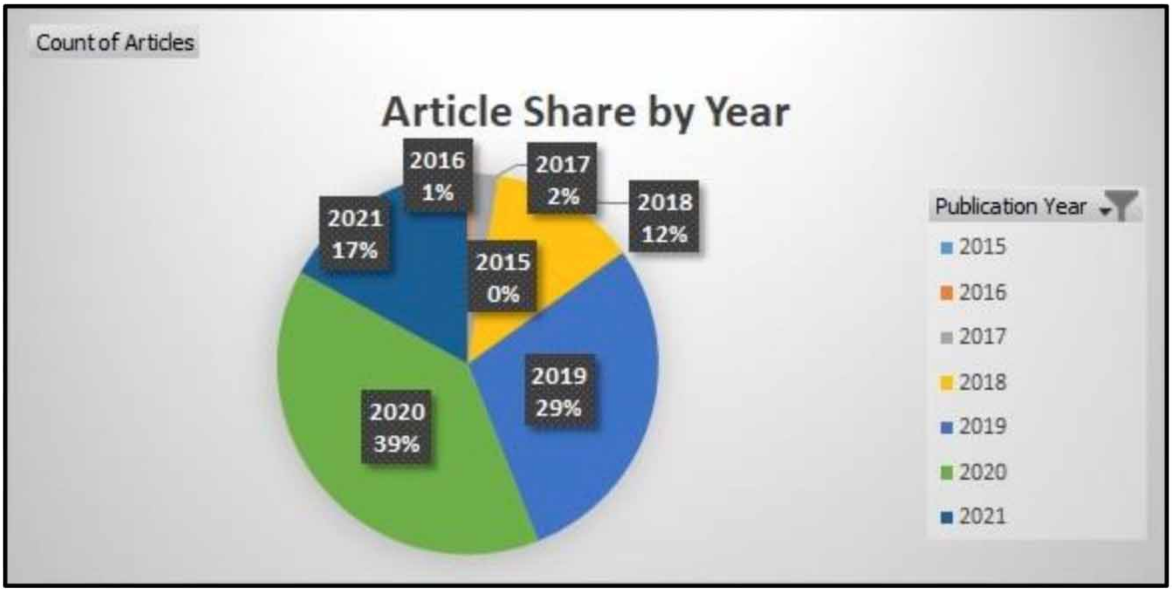


Fig. 7 | Blockchain & Water Management in IEEE Xplore.

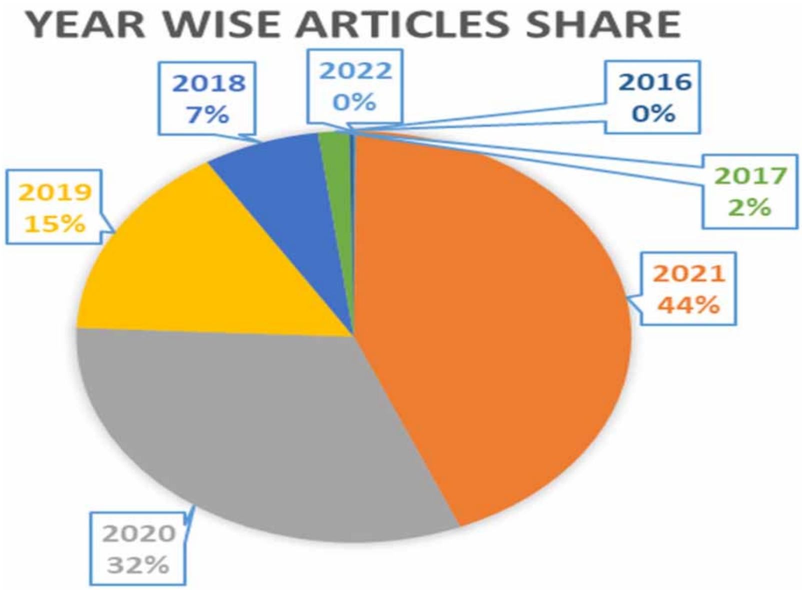


Fig. 8 | Blockchain & Water Management in ScienceDirect.

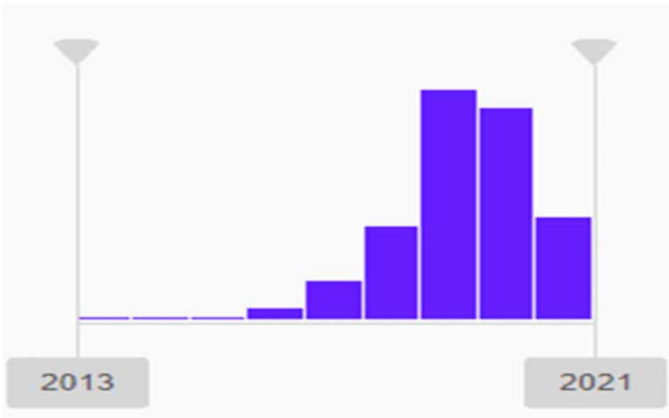


Fig. 9 | Blockchain & Water Management in ACM Digital Library.

industry. This study proposed an integrated pricing model for irrigators to sell water rights to industrial users through saving water from conservation methods. Huang *et al*. (2017) analysed the distribution of virtual water exports/imports across all regions of China. The authors estimated that the total export-related virtual water in China was 106.3 billion m^3. However, they were distributed unevenly across various regions of China. They observed that the eastern region employed efficient water usage methods in virtual water exports. Wu *et al*. (2018) argued about the importance of regional economic systems using virtual water as a tool. The authors proposed virtual water trading through import from water-abundant areas, which would help overcome regional water shortages. Virtual water promotes water efficiency and drives water flow to the service and

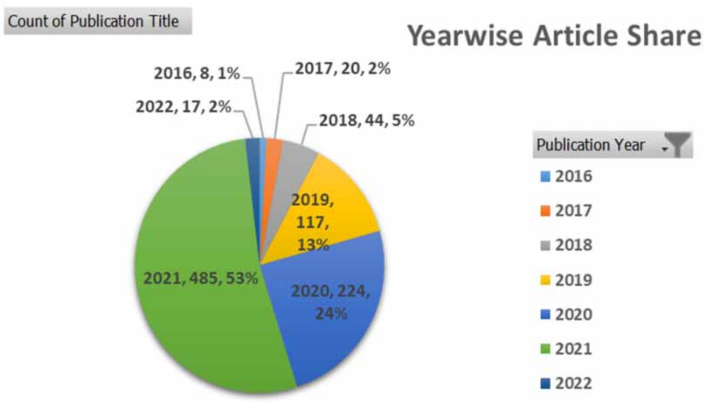


Fig. 10 | Blockchain & Water Management in SpringerLink.

industry sectors. Wu *et al.* (2021) conducted a water footprint analysis study in southwest China and found the least water footprint for rice production (Yunnan area) and the highest in the northeast. Northeast was at high risk. The authors argued in favour of framing better policies for groundwater extraction and international trade to ensure sustainable food supply and water use at regional and national levels. Wang *et al.* (2019) considered the import of virtual water as one of the future efficient methods for the import of low-efficiency crops and the development of high-efficiency agriculture and for the increase of water conductivity.

Kumar & Jain (2011) quantified virtual water export and import among various states of India to/from a central pool. This paper suggested that virtual water export should not be dependent exclusively on water availability but should also consider various factors like productivity, land availability, reforms, infrastructure, entrepreneurship culture and credit system availability.

Janjua & Hassan (2020) presented a weighted bankruptcy methodology for better management and sustainable sharing of water resources. Zeng *et al.* (2015) developed a two-stage interval-stochastic water trading (TIWT) model for limited water resource allocation to competitive users by the market approach. This approach helps to improve economic efficiency and provides remedies for water deficiency.

Manshadi *et al.* (2015) argued that virtual water transfers should satisfy both economic and environmental objectives and needs. The authors developed a model meeting economic, equity and environment criteria in order to lead to sustainable development. They suggested a cooperative game approach for best reallocation of net benefits. Similarly, Sepúlveda (2015) discussed relationships between export/import product balances and hydrologic footprint analysis. The author drew a comparison between global and local consumption patterns using the water footprint method and highlighted the importance of ecological economics.

Wu *et al.* (2018) conceptualized the importance of the virtual water strategy for promoting regional water security and better living standards. They opined that industrialization is becoming a competitor for agriculture. Virtual water brings better water efficiency. The authors advocated for the development of a 'virtual water integrated water resource management system', a useful system to trade virtual waters among regions. The authors found that arid regions greatly benefited from importing virtual water.

Reutter *et al.* (2018) assessed the flows of virtual water through the supply chains of the entire Australian economy. The authors proposed the Input Output foot printing methodology and assumed water footprint for any specific industry allocated in terms of the total sales to each customer.

Youkhana & Laube (2009) discussed the importance of importing food from water-rich countries as a sustainable solution for water-stressed regions. The authors argued that a strong political will, education and financial reforms were needed for better implementation of virtual water trade. Selim & Abdalbaki (2019) analysed virtual water export structure in the Nile basin countries. Kenya succeeded in saving a significant amount of virtual water, whereas a few other countries incurred losses. The authors employed social networking analysis to derive these statistics. Lopez-Gunn *et al.* (2012) argued that water and food cannot be isolated from socio-economic/political aspects. Water security, food security, human security and environment security cannot be handled independently. They are totally intertwined and they need to be looked at from the ethical perspective as well. The authors argued that understanding virtual water trade will lay the foundation for future water and food security.

Parveen & Faisal (2004) discussed the significance of virtual water trade in the context of food security. The authors asserted that food security is redefined as 'food self-reliance' instead of 'food self-sufficiency'. Deng *et al.* (2018) analysed the growth of food water footprint in China between 1997 and 2011. The authors advocated a green channel for the development of domestic food trade and virtual water trade.

Economic and climatic conditions play a major role in virtual water trade. Hassan & Thiam (2015) employed an economy-wide framework to evaluate virtual water flows. The authors recommended higher water-use efficiency and improved competitiveness of dryland agriculture in order to achieve food security. Berrittella *et al.* (2008) proposed to study water tax policies on international trade. Water taxes produce more efficiency, shifts in production, consumption and international trade patterns. Emmanuel & Clayton (2017) proposed virtual water trade to be incorporated in water policy. The authors argued that a country need not be water rich if virtual water trade is employed.

Chen *et al.* (2019) examined virtual water in terms of the water-energy nexus ratio. The authors assumed virtual water as hidden flows of water for electricity generation and transmission from other places. They observed that the eastern region of China is associated with not only high economic costs but also high-virtual water, energy usage and carbon emissions, which impact environmental and social costs.

Acheampong *et al.* (2016) proposed an integrated water resource management (IWRM) with a decoupling strategy. They discussed virtual water trade in the context of such a strategy. This aims to transform water management processes to achieve economic efficiency, social equity and environmental sustainability.

Mamo (2015) presented a basic decision support model for the prioritization of mitigation with better-informed and collective judgements. Wicaksono *et al.* (2017) argued for the development of a decision support system that will simulate and quantify water, energy and food interactions. Using this system, a sustainable development model can be created, evaluated and optimized. Doeffinger *et al.* (2020) presented their case for developing a diagnostic dashboard to understand the status of water security on the lines of the medical diagnosis process.

Further, Table 3 outlines the broad research topic suggested by various authors.

Part 2: Blockchain and water management findings

We further conducted a literature review on how blockchain is leveraged in the water management domain. Table 4 summarizes the critical review areas.

Blockchain supports a shared process with trusted data across all boundaries. This is quite important in the supply chain where location identification, origin and delivery confirmation and accuracy is critical. Of late, there is the practice of the creation of a traction in the area of water management using blockchain technology. However, it is observed that there is no major evidence about virtual water management using blockchain. Blockchain architecture is quite vital to build a Virtual Water International Trading System with Virtual Water Credits exchange (Ravi & Jayasri, 2015).

Table 3 | Research areas from virtual water perspective.

Sr. No.#	Key area	Author(s)
1	Water resources management process; Water valuation for decision making	Hellegers & van Halsema (2019)
2	Inequality of water use can be alleviated by the transfer of virtual water and the enhancement of WUE (Water-Use Efficiency)	He *et al.* (2020)
3	Virtual water trade (VWT) is a potential solution for water-stressed countries	Rogers *et al.* (2004); Oki & Kanae (2004); Johannessen (2004)
4	Variables connected to virtual water imports: Average income, Population, Agriculture as value added, Irrigated area, Exports of goods and services	Ramirez-Vallejo & Rogers (2004)
5	Establishment of an international virtual water trading council	Rahman *et al.* (2002)
6	Food Miles (the distance that food is transported from the time of its making till it reaches the consumer) and virtual water for urban management	Liebman *et al.* (2011)
7	Diet changes impact water footprint in a particular region; Winery water footprint calculation and wastewater calculation	Vanham & Bidoglio (2014); Saraiva *et al.* (2019)
8	The need for Virtual Water Credits and a Trading System	Ravi Shankar & Jayasri (2015)
9	Estimation of the virtual water trade between two regions; Analysis of Virtual Water consumptions for sustainable cities' development; water footprint (WF) from production and consumption perspectives and importing water-intensive agricultural products	De Miguel *et al.* (2010); Vanham (2011); Kang *et al.* (2017)
10	Redesigning existing water pricing policies using a virtual water strategy	Hristov *et al.* (2015)
11	A multi-region computable general equilibrium (CGE) model is devised using Virtual Water inflow and outflows. The authors analysed the GDP effect and employment rate in the context of Virtual Water flows	Zhao *et al.* (2021)
12	The material flow analysis method employed in evaluating spatiotemporal variations of the Water Resources Metabolism Efficiency (WME). Useful for improving the metabolic efficiency of both physical and virtual water.	Meng *et al.* (2020)
13	How virtual water is to help water stress management; intensity of the water footprint (Iwf) and the external water dependency (WD) in the context of Virtual Water trade	Huang *et al.* (2019); Sun *et al.* (2016)
14	Water rights trading scheme; a pricing model for the transfer of water rights from agriculture to industry in water-deficient areas for the healthy development of future water markets	Zhang *et al.* (2019)

Proposed international virtual water trading system using blockchain technology

As noted previously, virtual water is the embedded water in a product, i.e. the water consumed in the production process. Virtual Water Trade is becoming a critical component of water management at global and regional levels, especially in regions where water is becoming a scarce element (Renault, 2002). The goal of a virtual water management system is to measure quantity and fluxes. Across the world, many products are transacted daily. Each product is made of multiple components, manufactured at multiple geographical locations, assembled and transacted. Hence, the embedded water supply chain is a critical element both for gauging sustainability and for ethical reasons. Product premium should be decided on the basis of the total embedded water transacted among regions. Product assemblers should also take into consideration the issue of embedded water movement

Table 4 | Research areas from blockchain from a water management perspective.

Sr. No.#	Key area	Author(s)
1	New water pricing options and policy action using Blockchain, Artificial Intelligence, smart concepts (smart metering, demand response) with benefits for both energy and water fields	Grigoras *et al.* (2018)
2	Water control system to efficiently manage and coordinate the use of water in communities. Blockchain technologies employed to build trust among community members and for commercial resource	Bordel *et al.* (2019)
3	An integrated platform for real-time control and monitoring for residential networks, with secure data management based on blockchain technology to manage water resources more efficiently	Pahonțu *et al.* (2020)
4	Develop a Smart Water Grid and smart water meters for real-time water consumption data. A user privacy protection scheme is developed using Blockchain and Machine Learning (k-means) by grouping users into clusters, and each cluster has a private blockchain to record the data of its members	Lalle *et al.* (2020)
5	IoT is used to measure water quality in industrial tanks, and upon any violation, appropriate penalty is imposed. Blockchain is used to maintain the transparency, integrity and reliability of the violation records	Alharbi *et al.* (2021)
6	Water Distribution Systems (WDSs) with a secure scheme that can preserve users' identification and data consumption using blockchain. Prevention of duplication of hydraulic and water consumption and seamless securing of data transfer and avoiding data loss from data tampering	Mahmoud *et al.* (2019)
7	Data storage and communication channel handled by the central authority; the interaction and decision making is governed exclusively by end nodes using blockchain	Predescu *et al.* (2019)
8	The role of open-source technologies in providing new possibilities for participatory water governance. This paper stresses on a socially and politically informed view of digital water, which is essential for sustainable development	Hoolohan *et al.* (2021)
9	Blockchain is useful in the supply chain process of any product, from its raw material stage to the end product stage. It demands traceability, transparency and security	Akram *et al.* (2020)
10	The core purpose of blockchain is to trace every transaction in the supply chain, and everybody monitors every transaction	Sander *et al.* (2018)
11	IoT (Internet of Things) in collaboration with blockchain can help in real-time monitoring.	Kumari *et al.* (2018)
12	Blockchain manages supply chain goals like low price, risk reduction, quality, etc.	Kshetri (2018)
13	Proposed private–public ledger architecture while considering the privacy requirements of trading partners and also provides visibility for critical decision making	Wu *et al.* (2017)

and mistrust before finalizing components for assembly. Such an exercise contributes hugely to sustainability. Consumers should also attempt to buy products with low embedded water.

Blockchain gives value to each actor (producers, brokers, transporters, processors, wholesalers, retailers and consumers) in the supply chain. It provides different incentives (great liquidity, improved access to insurance, finance and other capabilities) to each type of actor. Blockchain (distributed data ledger) facilitates the recording and storing of every transaction (a cryptographically signed block structure) over the network (replicated over network participants). Each block has a hash and converts whole content into some random letters/numbers. Users can trust the data by validating them mathematically. Each actor can act as a node and participate in consensus building. Consensus takes place using complex algorithms. Each block stores the most critical information and minute details like the actual transaction details (Christine *et al.*, 2018).

General rules:

- Each product component manufacturer registers with blockchain (e.g. location details, product component manufacturing status, etc.).
- Every product component carries a product id and embedded water (an approximate amount of water per unit that would be consumed during its production process).
- The product assembler (manufacturer) generally chooses components on the basis of quality, price, etc. However, the manufacturer gets an opportunity to check an additional parameter called 'embedded water' before finalizing components for assembly.
- Blockchain stores all transactions over the network, reducing the need for third-party verification.
- Each component owner can view other component owners' data, thus potentially reducing the complex and costly reconciliation of the data process. This brings transparency and trustworthiness voluntarily. This reduces the risk of counterfeit products as well. This makes all parties agree to the smart contract, which is a critical feature of blockchain. It enforces all participants to agree to rules and processes that can facilitate, verify and execute the terms of an agreement.
- Highly sensitive information can be maintained in separate private ledgers along with public ledgers. Private ledgers are shared only among trustworthy partners. Partners are driven by memorandum of understanding (MoU). This feature is optional and not elaborated in the block diagram shown in Figure 11.

The diagram depicts the high-level blockchain transact view. Every product consists of multiple components. Each component is manufactured in a particular geographical condition or area. Further, each component is made up of a few other components. This chain can go up to the point of raw material use. For the sake of simplicity, the picture depicts only one layer of the product make. Downstream supply chain traceability is not depicted, again for the purposes of simplicity. Each component needs some embedded water for manufacturing. As part of the proposal, component manufacturers should announce appropriate embedded water needed to make their piece. This appropriation can be made by using the total quantity of water consumed in a particular year by the total number of components made. If all competitors declare their water usage data, trust can be built, and they will be both foolproof and tamper-proof. Hence, there is the possibility of declaring original values. Once data are disclosed over the blockchain, they become a permanent feature. Component owners should declare data carefully; otherwise, even if they want to correct them in future, they will find it difficult as they will become tamper-proof. So, this increases self-responsibility.

A typical block contains the company id, geographic location, embedded water used to manufacture a component and a link to blocks containing other components (a product is a combination of various components) if any, as shown in Figure 12.

Key highlights of the process:

- We are proposing a public blockchain. All transactions on a blockchain are cryptographically verified (by a distributed consensus mechanism) and sealed by three entries (seller, buyer and blockchain) (Nick, 2021).
- Transactions in a group are collected into a block that is validated by a third party called miner.
- A new transaction enters into the chain. This transaction is transmitted to a network of computers spanning across the world. Computers solve certain complex algorithms and approve transactions, which are allowed as block(s).

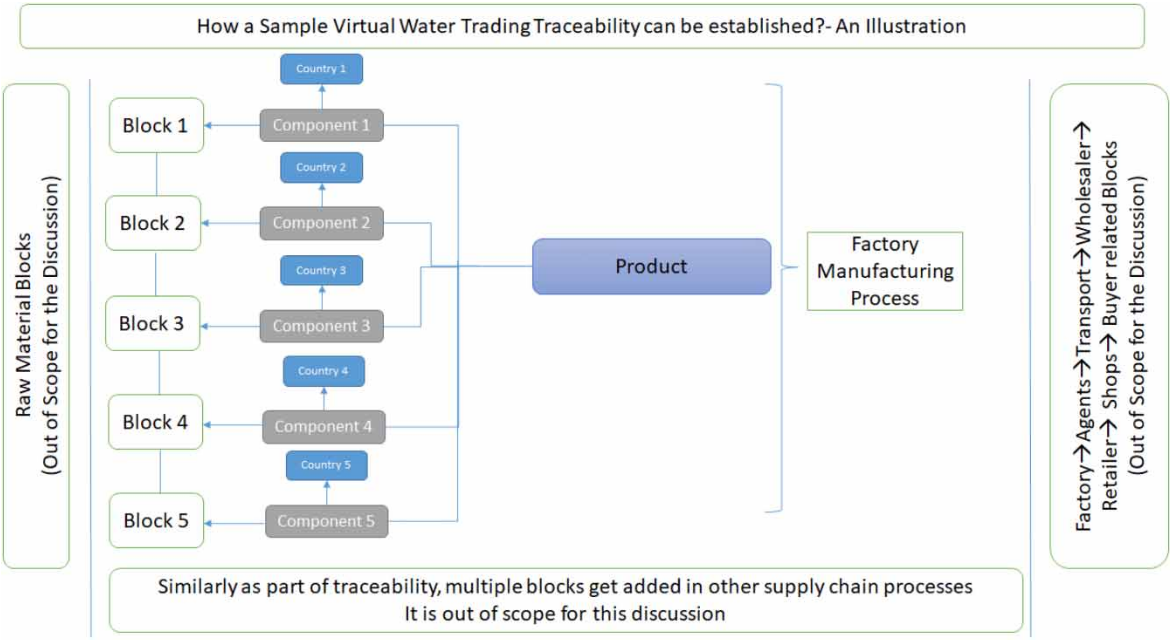


Fig. 11 | Virtual water-blockchain trading block diagram.

- The first block is called the Genesis block. Each new block is linked to a previous block key. The genesis transaction is the start of an order. It is initiated by the customer, who is assigned an admin node, and is broadcasted to all competitors (similar component owners) and product assemblers (who order these components for assembling a product).
- Each block contains a hash. Once a block is created, any change effected to the data makes the block and the corresponding chain invalid. Hence, they are tamper-proof.
- Hashing and Proof-of-Work together makes a blockchain secure. Tampering can happen in lightning speed. To avoid this, blockchain introduces a concept called Proof-of-Work. Consensus mechanism means proof-of-work (PoW) or mining or proof-of-stake (PoS). This is a special mechanism (computational problem) to slow down the speed of the new block creation. Hence, hackers cannot tamper with the entire chain.
- Additionally, blockchain uses a distributed peer-peer network (a copy of an entire blockchain is replicated), which further secures the process. Each computer in the network is called node. Each node adds a new block after a thorough verification. This process is called consensus. All nodes agree upon adding any new additional block, as shown in Figure 13. If there is any tampered block added, the nodes reject that block.

Fig. 12 | Virtual water-blockchain data structure.

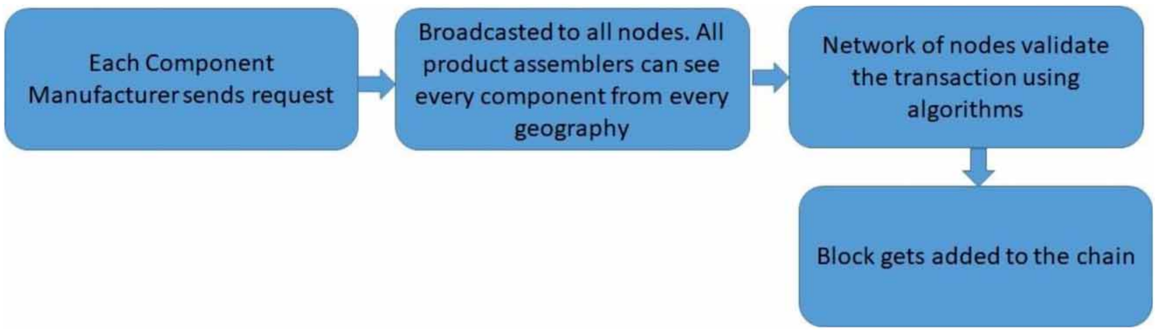


Fig. 13 | Virtual water-blockchain transaction process.

This process highlights the importance of importing or producing any product based on virtual water and its value in terms of time and space. It helps in defining water policies at a government and organization level.

THREATS TO VALIDITY

This research is constrained by a couple of biases (authority and publication). This research values the opinions of other researchers, which may be wrong. The results of the publications mentioned herein may be biased towards positive results. The search string used ('Virtual Water' and 'Blockchain & Water Management') may have multiple synonyms, but we de-risked this threat by manually verifying each and every result and also conducted a manual search on the basis of this search string.

CONCLUSION

A water-sensitive or water-conscious product design, manufacturing and trade preserves our environment. Water efficiency also profoundly impacts the operating costs and becomes a business imperative. Product labelling in terms of water usage increases public awareness. Product digital traceability aids in this process and makes it a transparent, safe and rich experience. So far, there have been no major linkages between international virtual water flows and product manufacturing processes. This is a new paradigm in water management. Blockchain technology seems to be the most promising in this context. It deals with various aspects like traceability, information transparency and product recall issues of the manufacturing process. Blockchain and virtual water management integration eradicates the counterfeiting of the components assembled in products. This process promotes the voluntary selection of water-efficient products or components and encourages the use of virtual water currency along with financial currency.

DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

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