Research Progress on Water Footprint Assessment of Agricultural Products: Postprint

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Abstract

Water footprint is an indicator measuring the quantity of water resources used directly or indirectly by consumers or producers, and has been widely applied in analyses of global or regional virtual water trade. This paper provides a relatively comprehensive review of research on water footprint assessment of agricultural products across different spatial scales, including global, national, and regional levels. Over the past decade, research on agricultural water footprints has shifted from focusing primarily on the analysis and evaluation of virtual water volumes in global agricultural trade before 2008, to emphasizing detailed accounting studies of direct and indirect water consumption during agricultural production processes at national or regional scales after 2009. Water footprint assessment exhibits pronounced spatial distribution characteristics; to obtain accurate, comprehensive, and objective information regarding the water footprint of agricultural production, it is imperative to consider influences from regional geographical features, soil physicochemical properties, climate change, production technologies, and pollutant ecotoxicity. Water resource management decision-making should comprehensively integrate the green, blue, and grey water footprints of agricultural products, as the blue water footprint of agricultural products characterizes direct consumption of societal freshwater resources and holds significant implications for international market trade decisions, while grey water footprint assessment more explicitly reflects the degree of environmental impact from agricultural production. Achieving the protection and sustainable utilization of agricultural water resources at global or regional scales requires not only improving water resource use efficiency in agricultural production, but also adjusting agricultural production structures, patterns and directions of virtual water trade in agricultural products, and reducing water resource waste during product circulation and dietary consumption.

Full Text

1.1 Water Footprint Definition

The water footprint is a volumetric indicator measuring water consumption and pollution [1], specifically referring to the total amount of direct and indirect water resources required for all products and services consumed by a certain region (a country, region, or individual) within a specific time period. Water footprint assessment comprises three components: blue water footprint, green water footprint, and grey water footprint. On one hand, it includes blue water resources stored in rivers, lakes, wetlands, and shallow groundwater layers (i.e., blue water footprint), as well as green water resources stored in the unsaturated soil layer and consumed through vegetation evapotranspiration (i.e., green water footprint). On the other hand, it includes the "grey water footprint" resulting from pollution.

1.2 Crop Water Footprint Accounting Methods

The water footprint during crop growth includes green, blue, and grey water footprints. "Green water" consumption refers to the total rainwater evapotranspiration in the field during crop growth, while "blue water" consumption refers to the evapotranspiration from field irrigation. The water footprint of agricultural products is primarily estimated based on crop water requirements, precipitation during the growth period, and irrigation water volume, using either the Cropwat model [27] or field experimental data. The green, blue, and grey water footprints consumed during crop growth are estimated through formulas (1)-(3):

$$WF_{proc,green} = \frac{CWU_{green}}{Y} \tag{1}$$

$$WF_{proc,blue} = \frac{CWU_{blue}}{Y} \tag{2}$$

$$WF_{proc,grey} = \frac{\alpha \times AR}{(C_{max} - C_{nat}) \times Y} \tag{3}$$

where $WF_{proc,green}$, $WF_{proc,blue}$, and $WF_{proc,grey}$ represent the green, blue, and grey water footprints consumed during crop growth, respectively, in $\mathrm{m}^3 \cdot \mathrm{t}^{-1}$; CWU_{green} and CWU_{blue} represent "green water" consumption and "blue water" consumption during crop growth, i.e., total rainwater evapotranspiration and irrigation evapotranspiration in the field, respectively, in $\mathrm{m}^3 \cdot \mathrm{hm}^{-2}$; Y is crop yield in $\mathrm{t} \cdot \mathrm{hm}^{-2}$; AR is the amount of fertilizer applied per hectare in $\mathrm{kg} \cdot \mathrm{hm}^{-2}$; α is the leaching rate, i.e., the proportion of pollutants entering water bodies relative to total chemical application, typically 10%; C_{max} is the maximum allowable concentration of pollutants in $\mathrm{kg} \cdot \mathrm{m}^{-3}$; and C_{nat} is the natural background concentration of pollutants in $\mathrm{kg} \cdot \mathrm{m}^{-3}$.

Pollutants typically include chemical fertilizers (N, P, etc.), herbicides, and pesticides. Calculations only need to consider the "wastewater flow" entering freshwater bodies, usually referring to the proportion of applied fertilizers or pesticides that enter water bodies from soil. Generally, only the most critical pollutant needs to be calculated—the one that produces the largest grey water footprint.

Additionally, the total amounts of green and blue water consumed during crop growth in the above formulas are calculated separately according to formulas (4)-(5):

$$CWU_{green} = 10 \times \sum_{d=1}^{lgp} ET_{green} \tag{4}$$

$$CWU_{blue} = 10 \times \sum_{d=1}^{lgp} ET_{blue} \tag{5}$$

where ET_{green} is green water evapotranspiration in mm; ET_{blue} is blue water evapotranspiration in mm; lgp represents the length of the crop growth period in days; and the constant factor 10 is the conversion coefficient to transform water depth (mm) into water volume per unit land area ($\mathrm{m}^3 \cdot \mathrm{hm}^{-2}$).

Crop green and blue water consumption is typically estimated based on the crop water requirement method. Using data on crop water requirements during the growth period (CWR, mm), effective precipitation during the same period ($Peff$, mm), and irrigation requirements (IR, mm) under specific climatic conditions, the green and blue water consumption of crops is determined using formulas (6)-(8):

$$ET_{green} = \min(ET_c, Peff) \tag{6}$$

$$ET_{blue} = \max(0, ET_c - Peff) \tag{7}$$

$$ET_c = K_c \times ET_{0-PM} \tag{8}$$

Irrigation water evapotranspiration equals total crop evapotranspiration (ET_c) minus effective precipitation ($Peff$), but its value is 0 when effective precipitation exceeds crop evapotranspiration. Crop green water evapotranspiration, i.e., precipitation evapotranspiration, is the smaller value between total crop evapotranspiration (ET_c) and effective precipitation ($Peff$); blue water evapotranspiration, i.e., irrigation evapotranspiration, equals total crop evapotranspiration (ET_c) minus effective precipitation ($Peff$), but its value is 0 when effective precipitation exceeds crop evapotranspiration.

The crop water requirement is estimated using the Penman-Monteith model [formula (9)] to estimate reference crop daily evapotranspiration and the crop coefficient method [formula (10)] to calculate crop evapotranspiration [28]. Crop irrigation requirement is calculated as the difference between crop water requirement and effective precipitation (i.e., equivalent to the degree of crop water deficit). If effective precipitation exceeds crop water requirement, irrigation requirement equals 0.

Formula (9) is the Penman-Monteith equation:

$$ET_{0-PM} = \frac{0.408\Delta(R_n - G) + \gamma\frac{900}{T+273}u_2(e_s - e_a)}{\Delta + \gamma(1 + 0.34u_2)}$$

where ET_{0-PM} is the estimated reference crop daily evapotranspiration total according to Penman-Monteith in $\mathrm{mm \cdot d^{-1}}$; $(R_n - G)$ is the total daily available energy in $\mathrm{MJ \cdot m^{-2} \cdot d^{-1}}$; R_n is the total daily net radiation in $\mathrm{MJ \cdot m^{-2} \cdot d^{-1}}$; G is the total daily soil heat flux in $\mathrm{MJ \cdot m^{-2} \cdot d^{-1}}$; γ is the psychrometric constant in $\mathrm{kPa \cdot {}^\circ C^{-1}}$; Δ is the slope of the saturation vapor pressure curve in $\mathrm{kPa \cdot {}^\circ C^{-1}}$; e_s and e_a are the saturation vapor pressure and actual vapor pressure, respectively, in hPa; T is the daily average temperature in ℃; u_2 is the daily average wind speed at 2 m height in $\mathrm{m \cdot s^{-1}}$; and K_c is the crop coefficient.

Under dryland agriculture conditions, the blue water evapotranspiration during the crop growth period is 0 (mm), and the actual water consumption of the crop (ET_a) is the green water evapotranspiration (ET_{green}, mm), estimated according to formula (7), while the blue water footprint is estimated according to formula (11):

$$WF_b = \frac{D}{Y}$$

where WF_b is the blue water footprint under dryland agriculture conditions; and D is the leakage amount in mm.

The water footprint of crops in protected facilities includes blue and grey water footprints. Water consumption within facilities is the blue water evapotranspiration, which can be calculated based on the soil water balance principle in facilities [formula (12)]:

$$ET = I + \Delta W - D$$

Generally, the terrain inside facilities is flat, and surface irrigation runoff problems are not prone to occur. Therefore, the influence of this part is ignored when estimating the blue water consumption of protected crops.

2 Current Status of Agricultural Water Footprint Assessment Research

The water footprint is an indicator measuring the amount of water resources used directly or indirectly by consumers or producers and has been widely applied in international and regional virtual water trade analysis research. Over the past decade, domestic and international water footprint assessment research (including virtual water trade) has shown a rapid growth trend. Based on the WOS database, a search using "Water Footprint" as the keyword retrieved 3,800 English literature articles on water footprint assessment from January 1996 to December 2016 [Figure 1a: see original paper]. Based on the CNKI database, a search using "水足迹" as the keyword retrieved 1,436 Chinese literature articles on water footprint assessment during the same period [Figure 1b: see original paper]. All retrieved literature was further classified, with 240 English articles on agricultural water footprint research identified in the WOS database, accounting for 6% of all English water footprint research literature, and 493 Chinese articles on agricultural water footprint research identified in the CNKI database, accounting for 34.3% of all Chinese literature. Based on the WOS database and classified by country, China' s agricultural product water footprint research reports rank second only to the United States, accounting for approximately 15.4% [Figure 2: see original paper], indicating that agricultural production and agricultural product water footprint and virtual water trade research have received widespread attention from Chinese scientists. Furthermore, WOS database searches revealed that agricultural water footprint accounting research before 2008 primarily focused on global-scale agricultural product water footprint assessment, with emphasis on virtual water accounting for crop import and export trade [25]. With increasing influence of water footprint accounting methods, regional climate change characteristics, and local production decisions on agricultural water footprint assessment research, detailed accounting studies of agricultural product water footprints for crops grown within national or regional spatial scales have become increasingly common after 2009, with even long-term field positioning trial methods for agricultural product water footprint assessment gaining attention [29]. Zou et al. [30] conducted detailed accounting studies of agricultural product water footprints for single or several crops at the national spatial scale in 2010. Overall, although reports on agricultural or agricultural product water footprint accounting research are relatively fewer compared to water footprint assessment studies in other industry sectors, they have also experienced rapid development in recent years.

Different planting industry agricultural products exhibit significant differences in production water footprint. Series studies on water footprints of major crop production processes at high spatial resolution show that corn has the lowest water footprint at 1,222 $m^3 \cdot t^{-1}$, wheat has the highest at 1,827 $m^3 \cdot t^{-1}$, and rice has a water footprint of 1,644 $m^3 \cdot t^{-1}$, approaching the average for all crops [[27,39-40]. Additionally, sugar crops and vegetables have relatively low water footprints at 200 $m^3 \cdot t^{-1}$ and 300 $m^3 \cdot t^{-1}$, respectively; fruit trees and oil crops have higher water footprints at 1,000 $m^3 \cdot t^{-1}$ and 2,400 $m^3 \cdot t^{-1}$, respectively; and legumes, spices, and nuts have the highest water footprints, ranging between 4,000-9,000 $m^3 \cdot t^{-1}$. The global water footprint during 1996-2005 was 9,087 $Gm^3 \cdot a^{-1}$, with green water footprint accounting for 74%, blue water footprint 11%, and grey water footprint 15% [41]. Agricultural production water footprint accounts for 91% of the global total water footprint, with crop production water footprint having the largest water consumption. For example, the global average water footprint for wheat production is 1,088 $Gm^3 \cdot a^{-1}$, with green water footprint accounting for 70%, blue water footprint 19%, and grey water footprint 11% [41].

2.1 Global Spatial Scale Agricultural Water Footprint

Hoekstra and Hung first conducted a global-scale water consumption assessment of several major agricultural products in 2002 [1], but this study did not separately account for green, blue, and grey water footprints of agricultural products [25]. Subsequently, Hoekstra' s research team and other researchers conducted a series of studies on global-scale agricultural product water footprints [1,4,8-9,23,31-36], pointing out that global agricultural product water consumption during 1997-2001 was 6,390 $Gm^3 \cdot a^{-1}$. Furthermore, crop virtual water consumption is far lower than product virtual water trade between different countries or regions, enhancing the dependence of water-scarce countries or regions on water-rich countries or regions, alleviating freshwater resource depletion in water-scarce countries or regions, and achieving water resource savings globally or within nations [38]. Sixteen percent of the global water footprint comes from external market trade of products [7]. Based on embedded product virtual water trade analysis, improving virtual water trade distribution patterns could save 222 $Gm^3 \cdot a^{-1}$ of water globally each year. Water footprint assessment studies on trade in goods and services between arid and semi-arid climate countries (Morocco) and humid climate countries (the Netherlands) found that international product virtual water trade activities from high water productivity to low water productivity countries or regions could save 6.4\$×10^{8}\$ $m^3 \cdot a^{-1}$ of water resources [10]. However, water savings from external virtual water trade also involve many disadvantageous factors and risks, such as reduced food self-sufficiency, decreased agricultural sector employment, and increased environmental impacts of export-import production [3].

2.2 National or Regional Spatial Scale Agricultural Water Footprint

In recent years, domestic and international researchers have extensively studied the water footprint assessment of major crop production such as cotton (Gossypium hirsutum L.), rice, and potato (Solanum tuberosum L.) at national or regional spatial scales. Research on cotton production water footprint (including grey water footprint) shows that the average water footprint of cotton production in 15 major cotton-producing countries is approximately 9,800 $Gm^3 \cdot a^{-1}$, with the United States having the lowest cotton production water footprint.

Except for China and the United States, most countries are water consumption-intensive cotton producers. Additionally, Brazil has a relatively low blue water footprint, possibly due to its abundant green water resources [31].

Crop water consumption in Indonesia accounts for 86% of the country' s total water consumption. Using nitrogen limitation standards from the US-EPA (2005) for grey water footprint calculation, coffee (Coffea sp.) has the largest water footprint at 22,907 $m^3 \cdot t^{-1}$ (96% green water, 0% blue water, and 4% grey water), followed by cacao (Theobroma cacao L.) with a water footprint of 9,414 $m^3 \cdot t^{-1}$ (94% green water, 0% blue water, and 6% grey water) [31], while cassava (Manihot esculenta Crantz) has the smallest water footprint at 514 $m^3 \cdot t^{-1}$. However, when comprehensively considering the cultivation area of crops in Indonesia, rice has the highest water footprint at 3,473 $m^3 \cdot t^{-1}$ (73% green water, 21% blue water, and 6% grey water) [31]. The average water footprint of oil palm (Elaeis guineensis Jacq.) in Thailand is 1,063 $m^3 \cdot t^{-1}$, with blue, green, and grey water accounting for 68%, 18%, and 14%, respectively. Oil palm production directly consumes relatively low blue water [42], but its virtual water flow is the largest [43]. Additionally, the production and consumption water footprints of coffee and tea [Camellia sinensis (L.) O. Ktze.] in the Netherlands are 140 $dm^3 \cdot cup^{-1}$ and 34 $dm^3 \cdot cup^{-1}$, respectively [44-45].

The average water footprint of potato production in the United Kingdom is 75 $m^3 \cdot t^{-1}$ (85% green water, 15% blue water) [15], Tunisia' s potato water footprint is 260 $m^3 \cdot t^{-1}$ (50% green water, 42% blue water, and 8% grey water) [46], Argentina' s potato water footprint is 324 $m^3 \cdot t^{-1}$ (56% green and blue water, 44% grey water) [47], and China' s sweet potato [Dioscorea esculenta (Lour.) Burkill] water footprint is 823 $m^3 \cdot t^{-1}$ (59% green water, 29% blue water, 12% grey water) [48]. From the aforementioned literature, we find significant differences in potato water footprints between different countries or regions, possibly related to differences in local climate conditions and agricultural management technical measures. Additionally, vegetable production water footprint assessment research primarily focuses on tomatoes (Lycopersicon esculentum Miller). The average water footprint of tomatoes in Spain is 81.3 $m^3 \cdot t^{-1}$, with a grey water footprint of 7.2 $m^3 \cdot t^{-1}$ [49].

2.3 China' s Agricultural Water Footprint

In recent years, a series of studies on agricultural water footprint assessment at China' s national and different provincial regional spatial scales have been conducted [FIGURE:1b, FIGURE:3], but they mainly focus on water resource utilization for grain production in water-scarce regions [14,16-18,20,50-51]. Among the agricultural water footprint assessment papers retrieved from CNKI, research papers on water footprint and virtual water trade of planting and livestock agricultural products account for 63.2%, while research papers based on industrial sector perspectives account for 36.8%. From a spatial scale perspective, research papers on provincial and municipal regions are the most numerous, cumulatively accounting for 51.5% [Figure 3a: see original paper]. Overall, 73.5%

of research papers primarily considered green and blue water footprints of agricultural products, 14.7% comprehensively accounted for green, blue, and grey water footprints of agricultural products, while research solely on grey water footprints of agricultural products is relatively scarce, accounting for only about 11.8% [Figure 3b: see original paper]. Given China' s severe water shortage, low water use efficiency in agricultural production, deteriorating agricultural water environment, and serious water resource waste, conducting agricultural product water footprint assessment research has important scientific significance.

Currently, approximately 67% of China' s agriculture is irrigated [16], and water resource consumption in agricultural production accounts for about 70% of total water consumption [52]. Hebei Province has the highest agricultural production water consumption among China' s provincial administrative regions, accounting for 96.35% of Hebei' s total water consumption [19]. Additionally, available water resources vary significantly among China' s different provinces, with Guangdong Province in southern China having the most at 27.5 billion $m^3 \cdot a^{-1}$, while Qinghai Province in northern China has the least at only 2.72 billion $m^3 \cdot a^{-1}$ [14]. During 1998-2000, China' s average grey water footprint was 481.43 billion $m^3 \cdot a^{-1}$, and economic effects were the main influencing factor for grey water footprint efficiency changes [53].

Research results on water footprint accounting analysis of 27 types of vegetables and animal products show that China' s per capita dietary consumption water footprint is 673 $m^3 \cdot a^{-1}$, primarily influenced by rice and pork products, and increased by 18 $m^3 \cdot a^{-1}$ due to food waste [17]. Therefore, in addition to changing unreasonable water use structures and reducing agricultural water footprints, attention should also be paid to reducing water resource waste and environmental significance.

Research results on agricultural product production water footprint assessment for China' s grain crops wheat, corn, and rice show that rice has the highest water footprint (1.36 $m^3 \cdot kg^{-1}$), while corn has the lowest (0.91 $m^3 \cdot kg^{-1}$) [54]. Rice' s water footprint is close to the global average level (1,325 $m^3 \cdot t^{-1}$) [8] but significantly higher than South Korea' s rice production water footprint (844.502 $m^3 \cdot t^{-1}$) [55] and lower than Indonesia' s rice production water footprint (3,473 $m^3 \cdot t^{-1}$) [31].

If only green and blue water footprints are considered, green water accounts for 57% and blue water 43% of the average water footprint of grain crops [16]. Insufficient precipitation resources severely affect wheat and corn cultivation and their water footprints in the Hetao Irrigation District. However, with improved irrigation efficiency, the blue water footprint in the Hetao Irrigation District decreased from 9.25 $m^3 \cdot kg^{-1}$ in 1960 to 0.79 $m^3 \cdot kg^{-1}$ in 2000 [56]. The aforementioned studies indicate that blue water consumption has an important impact on agricultural product water footprints, which is further confirmed in research on water footprints of cereal crop production [57-58]. Additionally, the main grain crop production water footprint in the Hetao region during 2005-2008 was 1.43-1.67 $m^3 \cdot kg^{-1}$, with a grey water footprint of 0.159-0.043 $m^3 \cdot kg^{-1}$, and both grain crop production water footprints and grey water footprints showed a 逐年 decreasing trend, possibly related to the promotion of water-saving irrigation and other new technologies [20]. Although China’ s corn water footprint level is lower than the global average, the proportion of grey water footprint is relatively large in some individual regions, indicating higher potential environmental pollution risks. For example, Beijing’ s corn production water footprint is 868 m^3 · t^{-1} (48.5% green water, 0.5% blue water, and 51.0% grey water) [48], indicating potential high environmental pollution risks in Beijing’ s corn production. Therefore, separate accounting of green, blue, and grey water footprints has important significance.

The wheat production water footprint in the North China Plain (Hebei, Beijing, and Tianjin) is 1.720$×10^{10}$ m^3 (green water 3.085$×10^{9}$ m^3, blue water 1.025$×10^{10}$ m^3, grey water 3.865$×10^{9}$ m^3). The corn production water footprint is 1.731$×10^{10}$ m^3 (green water 1.011$×10^{10}$ m^3, blue water 2.692$×10^{9}$ m^3, grey water 4.509$×10^{9}$ m^3). The total water footprint of wheat and corn production is 2.2 times the total available water resources in the North China Plain (1.549$×10^{10}$ m^3 in 2007) [50]. Therefore, to alleviate current water resource pressure in the North China Plain, improving water resource utilization efficiency alone is far from sufficient; adjusting agricultural production structure is the key.

Research on water footprint trends in different regions of China based on input-output models shows that the central region has the largest water footprint. The direction of domestic virtual water trade in different regions was inconsistent between 2002 and 2007. In 2002, virtual water net export regions were southern coastal, central, northwestern, and southwestern regions, while in 2007, virtual water net export regions were northeastern, northwestern, and Beijing-Tianjin regions [59]. Additionally, during 1992-2008, China net imported approximately 2.0$×10^{9}$ m^3 of virtual water in grain annually [60].

Beijing is one of China’ s cities with severe water shortages, with a blue water footprint of 4.498$×10^{9}$ m^3 · a^{-1}, 51% of which is virtual water input from other regions. Beijing’ s agricultural product water footprint is 1.524$×10^{9}$ m^3 · a^{-1}, with approximately 56% coming from other regions [61]. Beijing’ s agricultural grey water footprint decreased from 9.4$×10^{8}$ m^3 · a^{-1} to 5.2$×10^{8}$ m^3 · a^{-1} between 1995-2009, a reduction of 45% [62]. Therefore, China’ s agricultural production should not only improve water resource utilization efficiency but also adjust virtual water trade patterns to achieve domestic water resource savings.

2.4 Fruit Production and Consumption Water Footprint

Currently, research reports on fruit production and consumption water footprint accounting are still relatively scarce. Based on the WOS database, 27 research papers have been retrieved from 2009 to present. In South Africa’ s Sundays River Valley watershed, the average blue water consumption for citrus (Citrus reticulata Blanco) is 58.7 Mm^3 in normal years and 89.2 Mm^3 in drought years [63]. Additionally, life cycle assessment (LCA) method-based research on water footprints of citrus and strawberry (Fragaria×ananassa Duch.) production in different countries shows that China has the largest virtual water consumption per unit yield of citrus, followed by Spain, Italy, and Brazil, while the United States has the smallest virtual water consumption per unit yield of citrus. However, virtual water consumption per unit area of citrus is similar in most countries, for example, both China and the United States are approximately 5,000 $m^3 \cdot hm^{-2}$. Therefore, the main reason for differences in citrus water footprints between different countries is due to different yields per unit area (China and the United States have yields of 7.5 $t \cdot hm^{-2}$ and 38.7 $t \cdot hm^{-2}$, respectively).

For strawberry production, Spain has the highest water consumption per unit area. Although the United Kingdom and Poland have similar water consumption per unit area (approximately 2,500 $m^3 \cdot hm^{-2}$), the United Kingdom has higher strawberry yield per unit area, resulting in lower water consumption per unit yield of strawberries in the UK and higher water consumption per unit yield in Poland [64-65]. Australia produces 44,692 t of mango (Mangifera sylvatica Roxb.) annually, with an average virtual water volume of 2,298 $m^3 \cdot t^{-1}$ during orchard production. However, serious losses occur during agricultural product logistics, causing an average annual waste of 26.7 Mm^3 of green water and 16.6 Mm^3 of blue water from mango production sites to households [66]. Thus, reducing losses and waste in agricultural product logistics is important for alleviating shortages of available freshwater resources.

3 Research Limitations and Prospects

Water footprint assessment results have obvious spatial distribution characteristics. However, due to the lack of detailed spatial geographic characteristic information, previous global-scale water footprint literature results cannot accurately reflect changes in the global water footprint and contain certain uncertainties [67], making it difficult to serve as accurate and effective indicators for water resource utilization management [5]. Therefore, to evaluate human occupation of water resources and the sustainability and equity of water resource utilization, future water footprint assessments must provide explicit temporal and spatial information. Since green, blue, and grey water footprints have different opportunity costs and impacts, global virtual water trade [68] and water footprints in product production processes should be accounted for separately. Additionally, agricultural product production water footprint accounting based on the virtual water method only considers water resource consumption and pollution amounts and cannot intuitively reflect the environmental impact of water footprints, while agricultural product water footprint assessment research based on the LCA method is currently not mature enough and needs further improvement [26,42,69-70].

Agricultural product grey water footprint assessment research mostly only considers a single factor, namely nitrogen (N) leaching (leaching rate = 10%), and its impact on environmental water quality, while ignoring the impact of pollutants such as phosphorus (P) and pesticides in agricultural production. However, research results based on the NEWS (global nutrient export from watersheds) model on grey water footprints of 1,000 river basins worldwide show that two-thirds of rivers have varying degrees of N and P pollution, with 54% of river pollution due to P exceeding standards and only 11% due to N exceeding standards [71]. Therefore, future grey water footprint accounting requires in-depth research on how to obtain reliable pollutant emission data including N, P, pesticides, etc., at large regional scales and scientifically account for corresponding water resource pollution amounts. Additionally, the selection of maximum allowable concentration indicators for water environments in grey water footprint accounting lacks local characteristics, often adopting allowable limits from US-EPA [45 mg(NO_3-N) $\cdot$ dm^{-3}], EPA drinking water standards (TN, 10 mg $\cdot$ L^{-1}), or EU [50 mg(NO_3-N) $\cdot$ dm^{-3}]. Domestic researchers also frequently adopt corresponding water quality standards specified in China' s "Groundwater Quality Standards" (GB/T 14848-93) and "Standard Limit Values for Basic Items of Surface Water Environmental Quality Standards" (GB 3838-2002).

Although Chinese agricultural production water footprint assessment research has achieved many important results in recent years, it still urgently needs strengthening. First, attention should be paid to agricultural water footprint accounting in two aspects: watershed water compensation and runoff, especially in regions with severe water scarcity, fragile water ecological environments, and serious agricultural production water environmental pollution. Second, strengthen and expand water footprint assessment research for major local or regional agricultural product production processes based on the LCA method to facilitate comparative analysis of different products, production stages, and products from different origins. Establish and improve information databases on production technologies, water-saving measures, pesticides, and different types of fertilizers during production processes of various agricultural products in different regions. Additionally, strengthen comprehensive research on carbon, nitrogen, and water footprints during agricultural product production, trade, and consumption processes to comprehensively and objectively evaluate regional agricultural production water resource utilization efficiency, sustainable development, and its environmental impact.

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