Supporting the implementation of the Regional Water Scarcity Initiative (WSI) in the Near East and North Africa (NENA) Region

Water Footprint Network Approach Linked to Strategic Crop Value Chains in Tunisia

Deliverables Report:

Activity 2.3.C: Normalized determination of economic water productivity along the value chain for strategic crops

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Contents

List of Acronyms

AWARE: Available WAter REmaining

CF: Characterization Factor

CTUh: Comparative Toxic Unit for humans

CTUe: Comparative Toxic Unit for ecosystems

EWP: Economic Water Productivity

FAO: Food and Agriculture Organization of the United Nations

ISO: International Organization for Standardization

LCA: Life Cycle Assessment

MVAD: Marginal Value Added of water

PWP: Physical Water Productivity

ReCiPe: Life cycle impact assessment method for midpoint and endpoint indicators

TVAD: Total Value Added

USEtox: UNEP-SETAC toxicity model

WF: Water Footprint

List of Tables

List of Figures

Key messages

Executive Summary

This methodological note presents an integrated framework for assessing the water footprint of strategic crop value chains under conditions of increasing water scarcity, with a particular focus on Tunisia. Agriculture is the largest consumer of freshwater resources in the country, while climate variability, recurrent droughts, and competing demands place growing pressure on limited surface and groundwater supplies. To support informed water management and sustainable agricultural development, the study combines two complementary approaches: a volumetric water footprint assessment based on the Stepwise Accumulation Approach and a water footprint impact assessment aligned with ISO 14046 and Life Cycle Assessment (LCA) principles.

The first approach quantifies blue, green, and grey water use at each stage of the value chain and links water consumption to both physical and economic water productivity. The second approach evaluates the potential environmental impacts of water use, including water scarcity, eutrophication, ecotoxicity, and human toxicity, using established characterization methods such as AWARE, ReCiPe, and USEtox. Case studies from the literature illustrate how water footprints accumulate along value chains and identify irrigation and processing stages as critical hotspots.

The results demonstrate that integrating volumetric and impact-based approaches provides a more comprehensive understanding of water use, productivity, and environmental risk than either method alone. While volumetric indicators support efficiency and water allocation decisions, impact-based metrics contextualize water use within local environmental constraints. Despite data limitations and methodological challenges, the proposed framework offers a robust and adaptable tool to inform policy, guide resource allocation, and support sustainability strategies in water-scarce agricultural systems.

Keywords

Water footprint; Life Cycle Assessment; ISO 14046; Agricultural value chains; Water scarcity; Tunisia; Blue, green and grey water; Environmental impacts; Sustainable agriculture

Highlights

• Agriculture dominates freshwater use in Tunisia, underscoring the importance of water footprint assessment for sustainable value chain management under increasing scarcity.

• The study integrates volumetric water footprint accounting with LCA-based impact assessment to capture both resource-use efficiency and environmental consequences of water use.

• Blue, green, and grey water footprints accumulate along crop value chains, with irrigation and processing stages frequently identified as critical hotspots.

• Linking water use to physical and economic water productivity enables more informed decision-making on resource efficiency and value creation.

• The combined volumetric–impact framework provides a strong basis for policy design, supporting the reconciliation of economic performance with environmental sustainability.

1. Introduction

Water is essential for sustaining life, as well as supporting economic activity and maintaining social stability. In Tunisia, where water resources are limited and unevenly distributed, efficient management is increasingly critical (Soula et al., 2021). Specifically, agriculture, a major pillar of the national economy and rural livelihoods, places significant pressure on these scarce resources (Chebil et al., 2019). Moreover, climate variability, recurrent droughts, and growing demand from irrigation and urban centers as well as industry intensify competition for water, thereby highlighting the need for integrated and informed management approaches (Soula et al., 2025). Furthermore, strategic crop value chains in Tunisia are both economically important and closely linked to the country's natural and social systems. Therefore, understanding how these value chains interact with water resources is crucial for identifying opportunities to improve efficiency, reduce environmental impacts, and support long-term sustainability (Shahnum and Shah, 2024; WFAT, 2025). Accordingly, the objective of this methodological note is to provide a systematic framework for assessing the water footprint of strategic crop value chains in Tunisia. To achieve this, it presents methodologies for quantifying water consumption, explains the data sources and analytical procedures employed, and demonstrates how the results can identify critical hotspots that inform decision-making. By doing so, this framework links water use with environmental and economic considerations, thereby supporting strategies that balance growth with sustainability and resilience in the agricultural sector.

2. Methods

This note employs two complementary approaches to characterize the water footprint along a crop value chain. The first approach quantifies both physical and economic water productivity at each stage using the Stepwise Accumulation Approach (Hoekstra et al., 2011). The second approach applies an impact-based assessment, following ISO 14046 and Life Cycle Assessment (LCA) principles (Gerbens-Leenes et al., 2021), to evaluate the potential effects of water use on environmental categories such as scarcity, eutrophication, ecotoxicity, and human health. By integrating these approaches, the note provides a comprehensive understanding of both water use, including its quantification and economic evaluation, and its associated environmental impacts across all stages of the value chain.

2.1. Stepwise Accumulation Approach (volumetric water footprint)

The assessment begins by defining the objective and identifying the stages of the value chain to be analyzed. System boundaries, functional units, timeframes, and geographical coverage are specified for each stage. Data corresponding to the selected study years are then collected, including water inputs and outputs, and relevant regional information. At each stage, blue, green, and grey water footprints are calculated using a stepwise accumulation method based on the Water Footprint Network methodology. Finally, hotspots are identified and prioritized by determining which stages or processes contribute most to overall water use and pollution, supporting targeted strategies to improve water efficiency and sustainability across the value chain. The full procedure is illustrated in Figure 1.

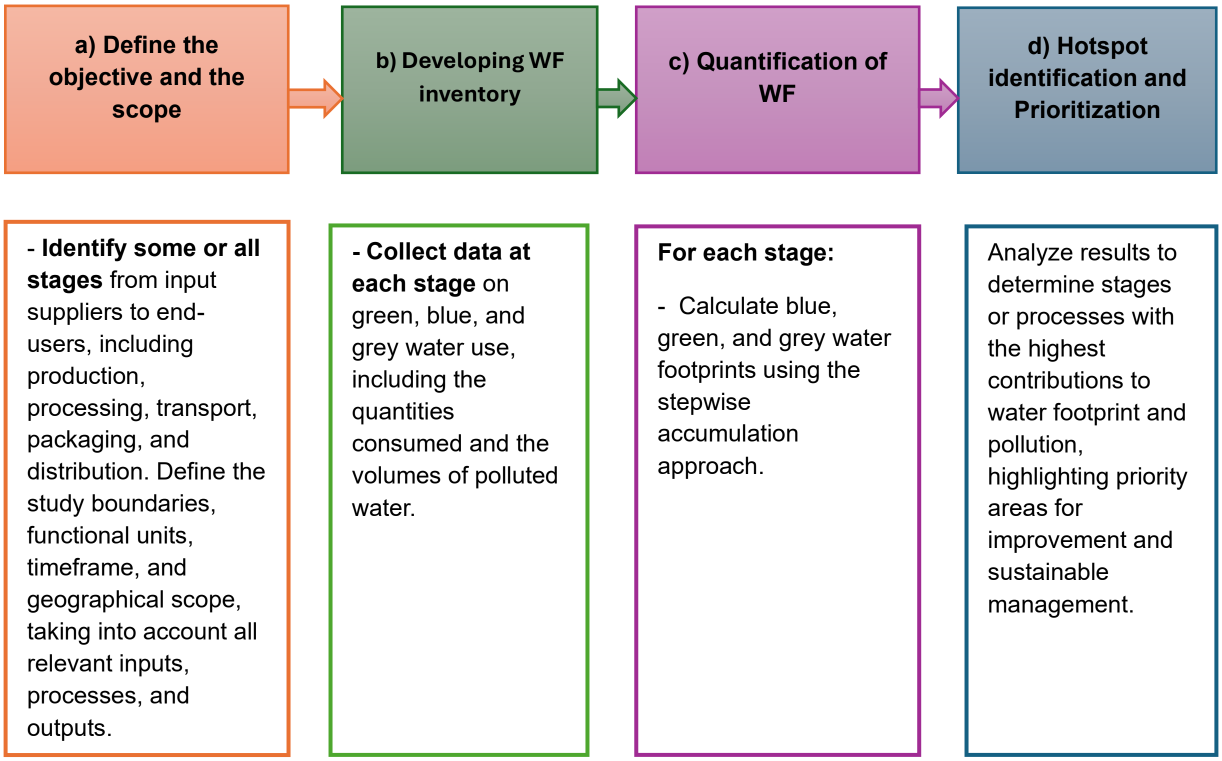

Figure 1. Procedure for Assessing the Water Footprint of a Crop Value Chain Using a Stepwise Accumulation Approach (adapted from Hoekstra et al., 2011)

2.1.1. Define objective and scope

The objective should clearly specify whether the study focuses on the entire value chain or selected stages, such as production, processing, transport, packaging, distribution, and consumption. System boundaries are established to determine which processes, flows, and interactions are included in the analysis, ensuring a clear and consistent framework for data collection and assessment.

2.1.2. Developing Water Footprint Inventory

The concept of the water footprint (Hoekstra, 2003), with the notion of grey water first introduced by Hoekstra and Chapagain (2008), has become a widely adopted tool in water resources management, providing a comprehensive measure of freshwater use across entire value chains. It accounts for both direct and indirect water use, which together encompass water consumption and water pollution. Direct water use refers to water withdrawn or consumed at the site of production, such as irrigation for crops or water used in manufacturing processes. Indirect water use refers to water embedded in upstream processes, such as water used to produce raw materials, energy, or other inputs required for the product. Water consumption includes the green water footprint, which measures rainwater stored in the soil and utilized by crops through evapotranspiration, and the blue water footprint, which quantifies surface and groundwater that is withdrawn and not returned to its source. Water pollution is represented by the grey water footprint, which estimates the volume of freshwater required to dilute pollutants, such as fertilizers, pesticides, or processing effluents, to meet acceptable water quality standards. Collecting detailed data on green, blue, and grey water at each stage of the value chain is therefore essential for producing an accurate and comprehensive assessment of a product's water footprint throughout the value chain (Figure 2, Table 1).

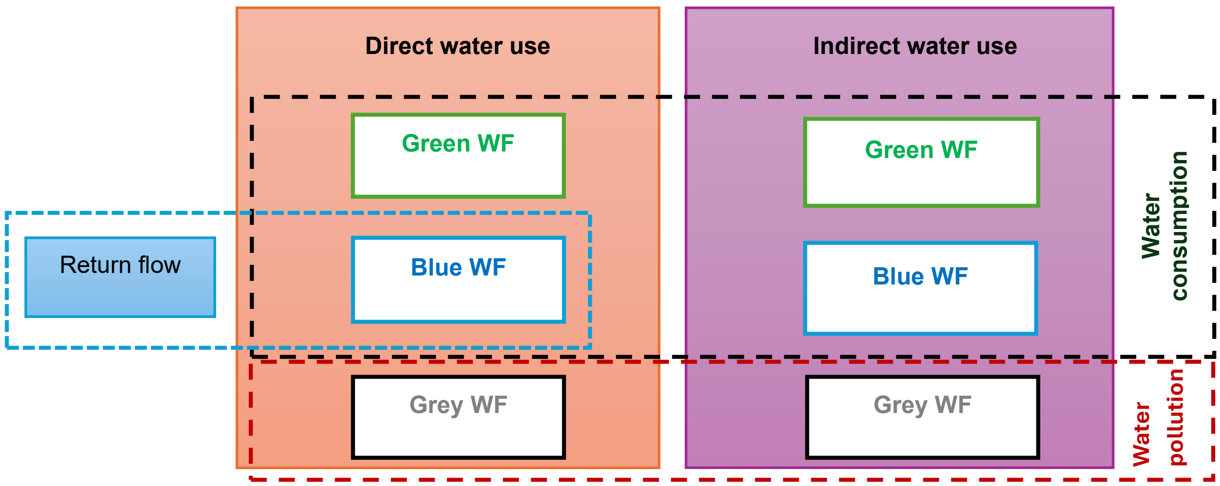

Figure 2. Water Footprint Inventory of a Product at a Stage of the Value Chain

Table 1. Green, Blue, and Grey Water Data for Water Footprint Assessment

Value Chain Stage	Blue Water (m³/ton)	Green Water (m³/ton)	Grey Water / Wastewater (m³/ton)	Relevant data Sources
Farm level / Cultivation	Irrigation from surface and groundwater	Rainwater consumed by trees via evapotranspiration	Water needed to dilute leached fertilizers and pesticides	(Souissi et al., 2019; Chouchane et al., 2013)
Mill / Processing	Water used for washing, crushing, pressing, and cleaning equipment	–	Wastewater from processing effluents, including oil residues	(Souissi et al., 2019; Gargouri et al., 2022)
Storage & Packaging	Water for cleaning storage tanks, bottles, and packaging operations	–	Wastewater from cleaning and sanitation	Industry reports (Tunisia & international)
Transport / Distribution	Water used in cleaning transport vehicles		Wastewater from cleaning and maintenance of transport vehicles	Industry logistics reports

2.1.3. Quantification of WF

The stepwise accumulation approach calculates a product's water footprint by integrating the water used at each stage of the value chain with the water embedded in its inputs. Because outputs from one stage often serve as inputs for the next, this method captures cumulative water use and pollutant generation across the entire production network. The calculation begins by quantifying the water footprints of input products and the additional water required to produce the outputs of the current stage. As illustrated in Figure 3, the water footprint of product p is derived from the footprints of y input products and the process water used to generate z output products, reflecting the accumulation across successive stages (Hoekstra et al., 2011; Arrien et al., 2025). Economic water productivity can also be calculated for each stage to support resource optimization.

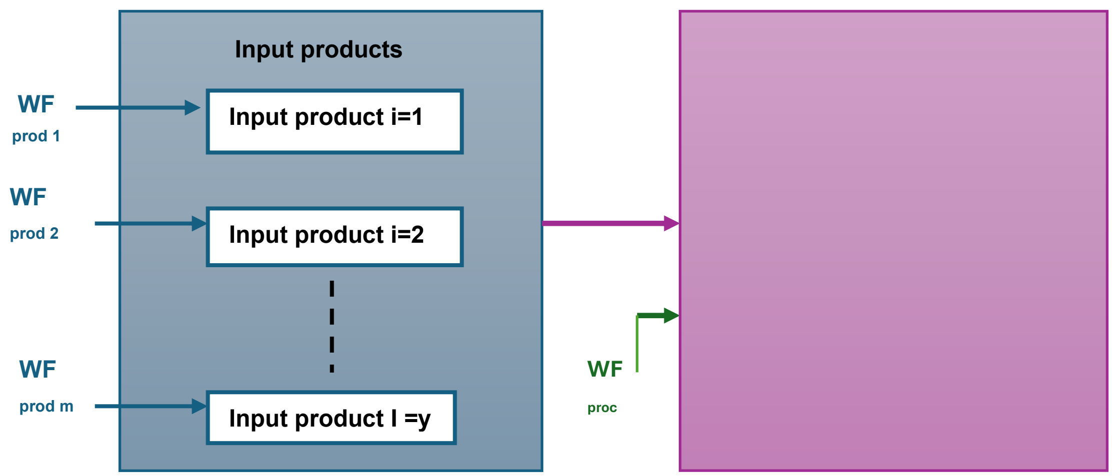

Figure 3 . Water footprint assessment in the production stage of a value chain (Hoekstra et al., 2011)

The total water footprint of an output product p, derived from $y$input products and producing z output products, is calculated as follows:

$$WF_{prod}[p] = (WF_{proc}[p] + \sum_{i=1}^{y} \frac{WF_{prod}[i]}{f_p[p,i]}) \times f_v[p] \qquad (1)$$

Where, $WF_{\text{prod}}[p]$is the total water footprint of product p in cubic meters per unit, $WF_{\text{proc}}[p]$is the process water footprint, and $WF_{\text{prod}}[i]$is the water footprint of each input product i.

Product fractions $f_p[p,i]$are commonly reported in the literature, for example by FAO (2003). However, it is important to note that the actual output per unit of input can vary depending on the production method (Chapagain & Hoekstra, 2004). For instance, in olive oil production, the proportion of oil obtained from olives depends on the pressing technique and extraction efficiency.

The product fraction $f_p[p, i]$quantifies the efficiency of converting an input into a specific output:

$$f_p[p, i] = \frac{w[p]}{w[i]} \tag{2}$$

where $w[p]$and $w[i]$are the masses of the output and input products, respectively.

The value fraction $f_v[p]$distributes water use according to the economic significance of each output:

$$f_v[p] = \frac{\text{price}[p] \times w[p]}{\sum_{p=1}^{z} \text{price}[p] \times w[p]} \tag{3}$$

where price$[p]$is the market price per unit mass of product p(in TND). This allocation ensures that water footprint assignments reflect economic importance rather than solely physical mass.

Because value fractions are influenced by market price fluctuations, it is recommended to use multi-year average prices to mitigate the effects of short-term variability.

Integrating the stepwise accumulation approach within a network-based value chain framework provides a comprehensive understanding of how water is consumed, reused, and polluted across interconnected production processes. By incorporating the combined blue, green, and grey water footprint equations, the method captures all major dimensions of freshwater use. This integrated framework enables the identification of water intensive stages within the value chain, supports the evaluation of both physical and economic water productivity, and provides a strong foundation for enhancing water use efficiency and sustainability across production networks (Mohlotsane et al., 2018).

The total process water footprint is expressed as the sum of the three components blue, green, and grey water, as shown in Equation (4):

$$WF_{\text{proc,total}} = WF_{\text{proc,blue}} + WF_{\text{proc,green}} + WF_{\text{proc,grey}} \tag{4}$$

The blue water footprint quantifies surface and groundwater consumed during production:

$$WF_{\text{proc,blue}} = \frac{CWU_{\text{surface}} + CWU_{\text{ground}}}{Y_t} \tag{5}$$

where $CWU_{\text{surface}}$and $CWU_{\text{ground}}$are consumptive uses from surface and groundwater, and $Y_t$is the total yield. The green water footprint represents rainwater stored in soil and used by plants:

$$WF_{\text{proc,green}} = \frac{CWU_{\text{green}}}{Y_t} \tag{6}$$

The total consumptive water use from both blue and green sources can be calculated as:

$$CWU_{\text{blue,green}} = 10 \times \sum_{d=1}^{lgp} ET_{\text{blue,green}} \tag{7}$$

where $ET_{\text{blue,green}}$is daily evapotranspiration (mm/day) over the growing period (lgp), and the factor 10 converts mm into m³/ha.

The grey water footprint accounts for freshwater required to dilute pollutants to acceptable concentrations:

$$WF_{\text{proc,grey}} = \frac{\alpha \times AR}{(c_{\text{max}} - c_{\text{nat}}) \times Y_t} \tag{8}$$

where $\alpha$is the leaching or runoff fraction, AR is the pollutant application rate (kg/ha), c_{max} is the maximum acceptable concentration (kg/m³), and c_{nat} is the natural background concentration (kg/m³).

The water footprint of a production process is strongly influenced by the technology that is applied. Water consumption, for example, varies between dry and wet processing methods or between open and closed cooling systems. Although the literature provides indicative estimates of water withdrawals, reliable data on actual consumptive use and pollution loads remain limited. These parameters can differ considerably depending on local environmental conditions, management practices, and process efficiency. Therefore, accurate water footprint assessments require the direct collection of data from producers, processors, and other facilities involved in the value chain.

Integrating all three components, the comprehensive process water footprint is expressed as:

$$WF_{\text{proc,blue,green,grey}}[p] = \frac{CWU_{\text{blue}}}{Y_t} + \frac{CWU_{\text{green}}}{Y_t} + \frac{\alpha \times AR}{(c_{\text{max}} - c_{\text{nat}}) \times Y_t} \tag{9}$$

This framework links consumptive and degradative water use, allowing unified quantification at the process level.

To connect water use with productivity, physical water productivity (PWP) measures the amount of product generated per unit of water used:

$$PWP(\text{kg/m}^3) = \frac{1}{WF_{\text{prod}}[p](m^3/tonne)} \times 1000 \tag{10}$$

The economic water productivity (EWP) accounts for economic value added per unit of product, expressed in TND/m3:

$$EWP(\text{TND/m}^3) = PWP(\text{kg/m}^3) \times VAD(\text{TND/kg}) \tag{11}$$

where VAD(value added per kg) is calculated as the difference between total revenue and total cost at a production stage j:

$$VAD_j = \text{Revenue}_j - \text{Cost}_j \tag{12}$$

The total value added (TVAD) across all stages of the value chain is:

$$TVAD = \sum_{j=1}^{m} VAD_j \tag{13}$$

The marginal value added of water (MVADwater) quantifies the additional economic return from an incremental unit of water use:

$$MVAD_{\text{water}} = \frac{\partial TVAD}{\partial WU} \quad (14)$$

2.1.4. Hotspot identification

In a crop value chain, water footprint hotspots are identified by assessing green, blue, and grey water use at each stage, including production, collection, milling, packaging, transport, and retail, while accounting for spatial and seasonal variations. This assessment enables precise calculation of water consumption and pollution, highlighting the stages or processes that contribute most significantly to overall water use and environmental impact. Identifying these hotspots allows for targeted management actions, such as enhancing irrigation efficiency, optimizing water reuse during processing, and minimizing fertilizer and agrochemical runoff. Implementing these measures promotes sustainable water management throughout the entire value chain.

Environmental hotspots in water resources occur when the demands of agriculture or industry compromise the availability or quality of water needed to sustain ecosystems. Green water footprint hotspots happen when rainwater stored in the soil is diverted from natural vegetation to crop production, potentially affecting biodiversity. For example, excessive irrigation or the expansion of cropland in sensitive areas can disrupt ecosystem balance. A common guideline is that at least 30% of the natural evaporative flow should be maintained to support ecosystems. Blue water footprint hotspots arise when withdrawals of surface or groundwater for irrigation, processing, or cleaning reduce environmental flows below the ecological requirements of a catchment. These situations are particularly critical during peak irrigation periods or in regions experiencing water scarcity. The main indicator is the ratio of annual water withdrawals to total annual runoff, with values above 100% signaling unsustainable use. Grey water footprint hotspots develop when nutrient runoff or agrochemical discharges from farms, processing facilities, or packing plants exceed local water quality standards, posing risks to freshwater ecosystems (Hoekstra et al., 2011).

Case study : Bread value chain

Mohlotsane et al. (2018) studied water productivity and value chain efficiency in South Africa, highlighting how water use and efficiency vary along the bread value chain, including physical and economic water productivity (Table 2).

At the wheat production stage, the crop uses 8,800 m³/ha of water, divided into green water from rainfall (1,830 m³/ha), blue water from irrigation (6,810 m³/ha), and grey water from fertilizers/pesticides (55 m³/ton). The total water footprint is 928 m³/ton, dominated by blue water, indicating that irrigation contributes the largest portion of water used in wheat cultivation (Table 2). Physical water productivity is highest at this stage (1.125 kg/m³), and economic water productivity is 4.5 ZAR/m³.

Table 2. Water Use Data at Wheat Production Stage

ET Crop **(mm)**	ET Green **(mm)**	ET Blue Surface **(mm)**	ET Blue Groundwater **(mm)**	CWU **(m³/ha)**	CWU Green **(m³/ha)**	CWU Blue **(m³/ha)**	Yield **(ton/ha)**	WF Green **(m³/ton)**	WF Blue Surface **(m³/ton)**	WF Blue Ground **(m³/ton)**	WF Grey **(m³/ton)**	Total WF **(m³/ton)**

880	183	681	0	8,800	1,830	6,810	9.9	185	688	0	55	928

During flour processing, wheat is converted into 632,348 tons of flour, using 46,053 m³ of water, primarily blue water from milling operations and minor grey water from processing waste. Water efficiency declines during this stage, with physical water productivity at 13.73 kg/m³ and economic water productivity at 78 ZAR/m³. The water footprint per ton of flour is 0.073 m³/ton, showing that processing is less water-intensive than cultivation, but efficiency is lower.

At the bread production stage, flour is converted into 379,803 tons of bread, using 17,447 m³ of water, mainly blue water for baking and minor grey water for cleaning. Physical water productivity is 21.8 kg/m³ and economic water productivity is 37 ZAR/m³. The total water footprint, including upstream processing, is 0.046 m³/ton, demonstrating that water efficiency continues to decrease in the final stage.

Physical and economic water productivity are highest at the crop production stage and decrease along the value chain, while water footprints accumulate. Blue and grey water dominate in the processing stages, highlighting the impact of irrigation and industrial water use on overall water consumption in bread production (Table 3).

Table 3. Summary of Water Productivity and Water Footprints along the Bread Value Chain

Parameter	Wheat	Flour	Bread
Yield	9.9 ton/ha	632,348 ton	379,803 ton
Total water use	8,800 m³/ha	46,053 m³	17,447 m³
Physical water productivity (PWP)	1.125 kg/m³	0.014 kg/m³	0.022 kg/m³
Value added	4.0 ZAR/kg	5.7 ZAR/kg	1.7 ZAR/kg
Economic water productivity (EWP)	4.50 ZAR/m³	0.08 ZAR/m³	0.04 ZAR/m³
Water type	Blue> Green > Grey	Blue > Grey	Blue > Grey
Water footprint (WF)	928 m³/ton	0.073 m³/ton	0.053 m³/ton

2.2. Water Footprint Based on Environmental Impacts

The impact-based water footprint was assessed following the ISO 14046 framework and the principles of Life Cycle Assessment. This approach aims to estimate and manage the potential environmental impacts associated with water use throughout the value chain. The assessment follows a structured process that begins with defining the objectives and scope of the study, continues with data collection and inventory development, and concludes with the evaluation of potential impacts, ensuring that the study's objectives are achieved with clarity and confidence (Forin et al., 2020; Figure 4). According to Osorio-Tejada (2022), the ISO 14046 standard allows the impact assessment phase to be omitted when the sole objective is to quantify water consumption in a water footprint inventory, which distinguishes it from more comprehensive Life Cycle Assessment studies.

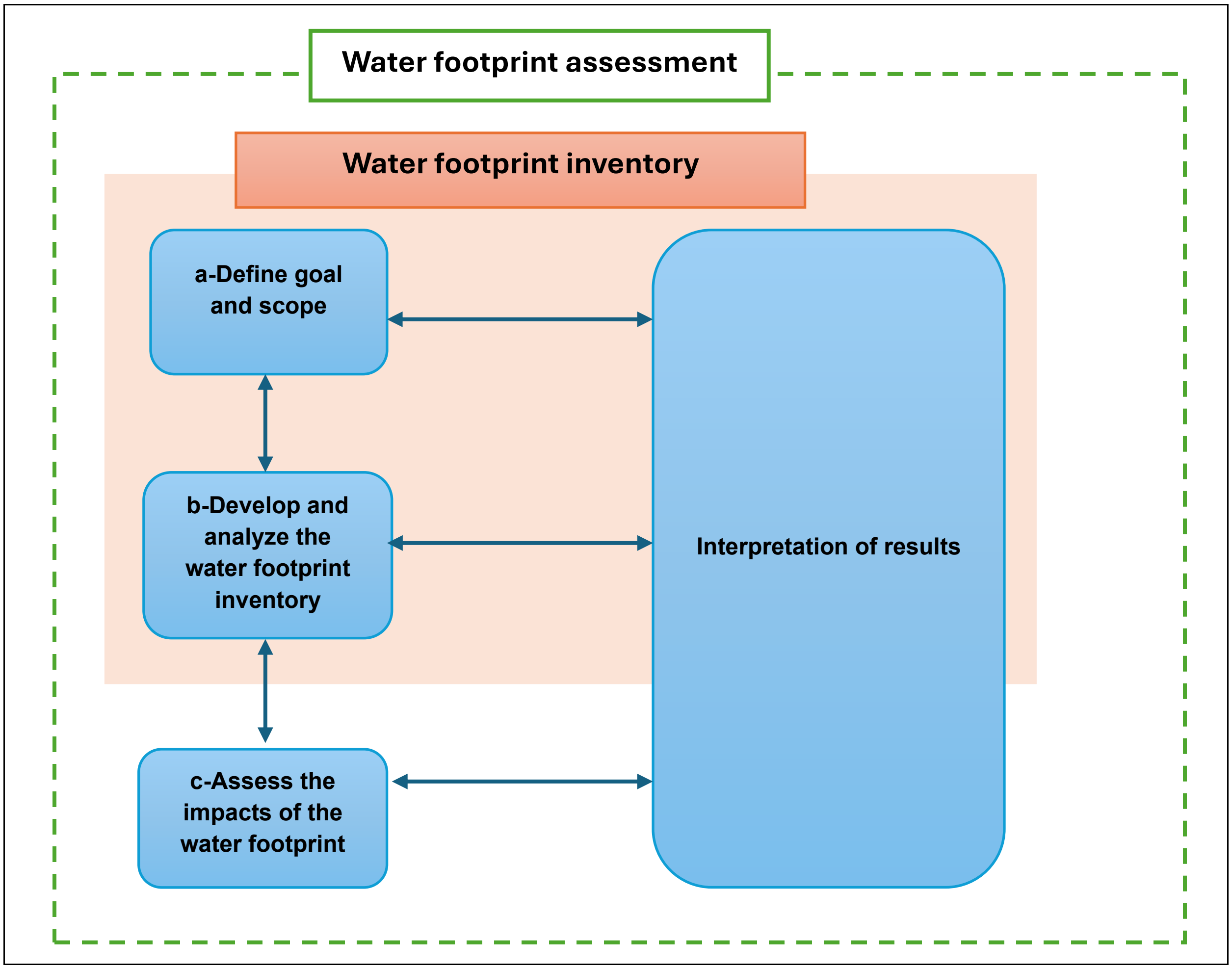

Figure 4. Steps in the assessment of a water footprint within a value chain based on ISO 14046:2014 (ISO, 2014) standard for LCA studies.

The gathered data should reflect the potential environmental effects of water use, including consumptive uses in which water is not returned to the watershed and degradative uses in which water quality is altered (Chaverri et al., 2017) (Figure 2). Since these impacts vary according to regional conditions such as soil type, climate, and local hydrology, the approach accounts for both quantitative and qualitative pressures on water resources. It also encompasses the assessment of direct water use, such as the water consumed during production processes, as well as indirect water use embedded in upstream activities, inputs, and materials throughout the value chain. Evaluating both forms of use is essential for obtaining a comprehensive understanding of the total water burden associated with a product or activity over its lifecycle (Figure 5). However, in this study, the Water Footprint based on the Life Cycle Assessment (LCA) tool is applied to illustrate how environmental impacts are evaluated specifically across the first and second stages of the value chain, which directly contribute to water consumption and pollution.

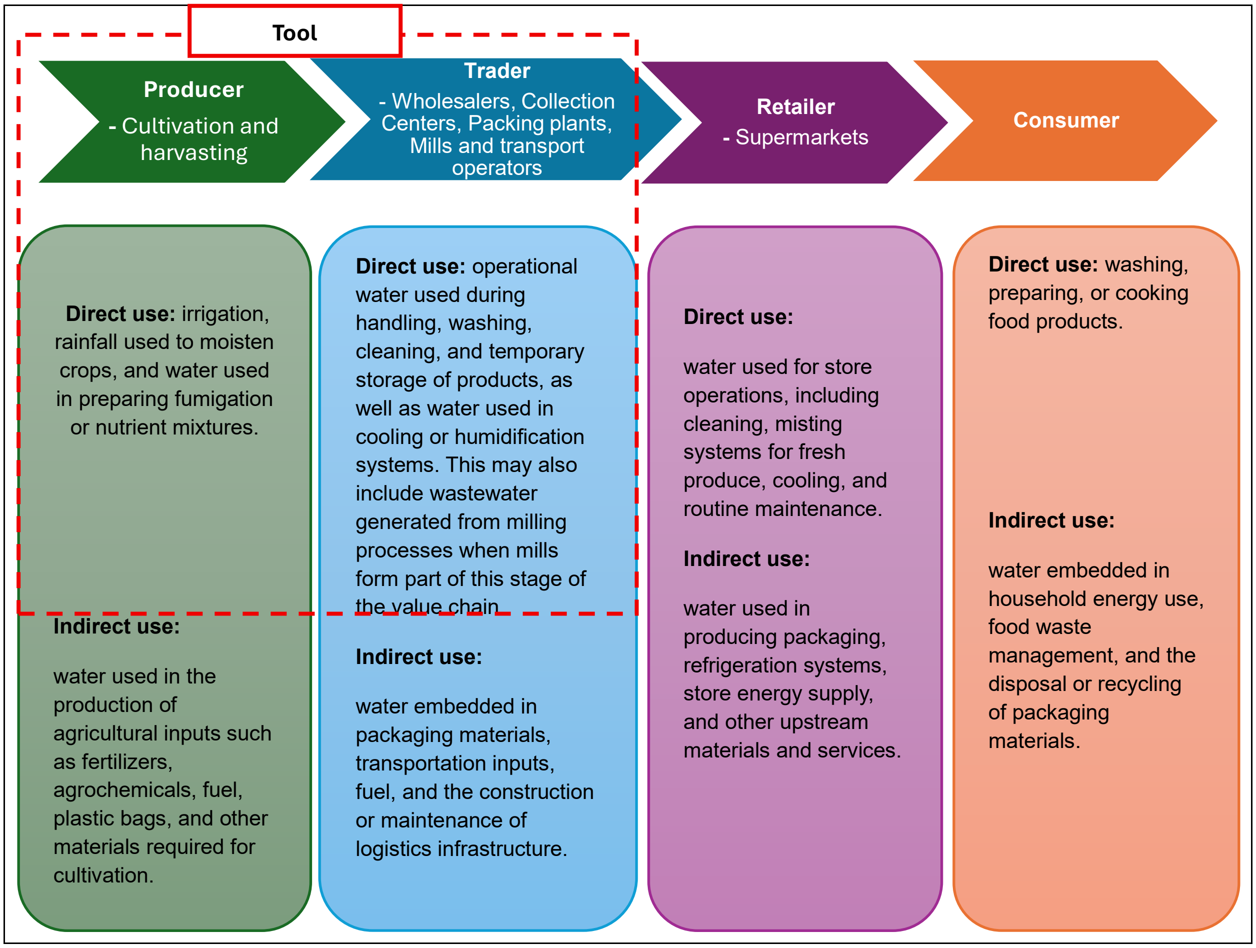

Figure 5. Direct and indirect uses of water in a value chain

Water consumption and pollutant emissions at each stage of the value chain can be systematically quantified and converted into potential environmental impacts. The key impact categories considered include water scarcity, freshwater and marine eutrophication, ecotoxicity, and human toxicity (FAO, 2024) (Figure 6). Integrating these categories allows for a comprehensive assessment of water footprints using appropriate indicators and facilitates the identification of critical hotspots where water use or pollution may pose the greatest risks to ecosystems and human health.

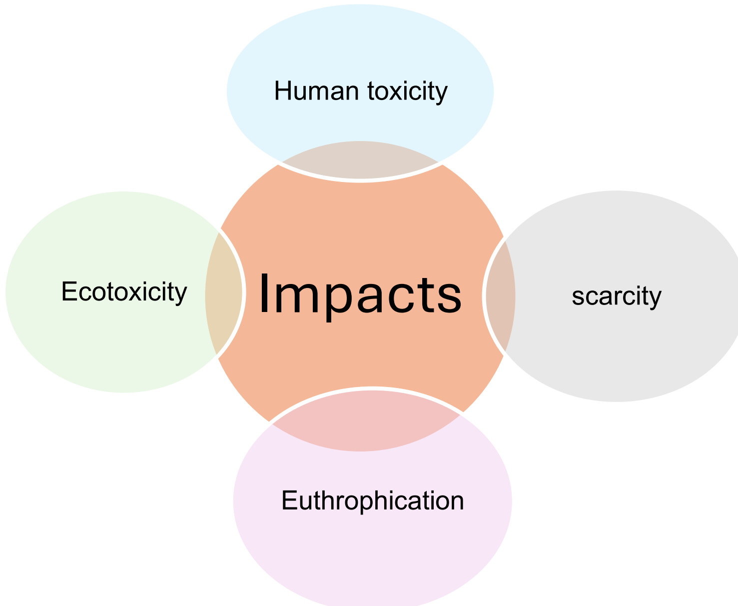

Figure 6. Impact categories recommended for the value chain.

2.2.1. Define goal and the scope

The goal specifies the purpose of the analysis, its intended use, target audience, and whether it is conducted independently or as part of a life cycle assessment. The scope defines the system boundaries, including the processes, facilities, geographic area, time frame, functional unit, and impact categories (Table 4). Establishing clear boundaries is crucial because water use and pollution can occur at locations and times different from where the product is consumed. Data are collected from both primary and secondary sources within these defined boundaries.

Table 4. Summary of goal and scope parameters used in the assessment (based on Chaverri et al., 2017)

Aspect	Description	Purpose
System and Boundaries	Specifies the stages, processes, and flows included in the study and defines the system boundaries. Clarifies whether the focus is on product and process.	Defines what is included and excluded in the assessment.
Functional Unit	The unit in which results are expressed, reflecting the performance of the product system. Includes reference flows used to produce the functional unit.	Establishes how and with respect to what the results are expressed.
Time and Geographical Coverage	Defines the period of study and the physical location. Regional data should be used to reflect local water availability, climate, and hydrology.	Indicates when and where the study was conducted.

Data and Quality, Assumptions	Specifies primary and secondary data sources, quality, and any assumptions or decisions made. Primary data preferred for accuracy.	Ensures reliability and transparency of the data used.
Potential Environmental Impacts	Identifies which impacts are considered or excluded, the impact assessment methodologies, categories, and indicators.	Clarifies the scope and methodology of impact estimation.
Limitations and Uncertainties	Defines limitations related to the functional unit, data quality, methodology, assumptions, exclusions, and other factors.	Describes factors affecting the certainty of the results.
Justification of Exclusions / Cutoff Criteria	Explains excluded information and cutoff thresholds (e.g., minor inputs below 5%).	Defines the extent of the study and rationale for exclusions.
Base Year	Specifies the first year used for comparison and data collection.	Provides a reference point for evaluating performance over time.

2.2.2. Develop and analyze the water footprint inventory

Primary and secondary data must correspond to the years selected for the study and encompass all relevant inputs and outputs, including water quantity and quality, chemical products, agrochemicals, fertilizers, production data, and geographic information for the study area. Primary data, obtained directly through measurements at each process, is preferred. When primary data are unavailable or difficult to obtain, well-supported secondary sources, such as literature, may be used. Direct water use activities include irrigation, spraying, plant evapotranspiration, agrochemical preparation, employee hygiene, and cleaning of fruit and equipment. Data sources include literature, calibrated water meters, wastewater volume estimates, records of agrochemical and fertilizer applications, and treatment plant discharge reports (Table 5 and Table 6).

Table 5. Information to be gathered in order to estimate the direct water footprint in the first value chain stage (farm planting and harvesting process)

Category	Data / Indicators	Data Sources
Water supply	- Volume and frequency of irrigation - Volume in spraying mixtures - Rainfall and climate data (precipitation, temperature, humidity, sunshine, wind)	• Farm records and water-meter measurements • National Institute of Meteorology (INM) • FAO CLIMWAT and local climate reports • National Institute of Statistics (INS) • Regional Agricultural Development Commissariats (CRDA)

		• National Observatory of Agriculture (ONAGRI)
Soil & plantation data	- Soil type and moisture - Rooting depth - Crop coefficient (Kc) - Critical depletion, crop height, yield response (Ky)	- Farm records - Tunisian Ministry of Agriculture, soil maps - Literature
Farm characteristics	- Total hectares - Watershed, water sources and discharge points	- Farm records - Geographical maps
Crop evapotranspiration	- Total evapotranspiration (m^3/year)	- CROPWAT FAO - Tunisian crop sector reports
Fertilizers	- Type and quantity (kg P, N, K, etc.)	- Fertilization programs - Application records - Laboratory tests and research
Agrochemicals	- Type, formulation, concentration, active ingredient - Quantity applied	- Spraying programs - Laboratory tests and research - reports
Wastewater / Pollution	- Runoff from fertilizers and pesticides - Mill or processing effluents	- Farm records - Local environmental reports - Water quality monitoring data

Table 6. Water Footprint Information for Trader Stages

Stage	Water Use	Wastewater / Discharge	Pollution / Organic & Agrochemical Load
Wholesalers	Cleaning storage areas, containers, and equipment	Wastewater generated from cleaning operations	Organic residues from products; agrochemical residues
Collection Centers	Cleaning bins, crates, storage areas	Wastewater from cleaning operations	Product residues, soil, organic debris; agrochemical residues
Packing Plants	Washing, sorting, and handling products	Wastewater from tanks, channels, or recirculation systems	Product residues (BOD/COD[1]); agrochemical residues
Mills	Washing, peeling, milling, and processing	Wastewater from processing steps	Product residues (BOD/COD); agrochemical residues

[1] BOD (Biochemical Oxygen Demand): BOD measures the amount of oxygen microorganisms need to decompose biodegradable organic matter in water. Its unit is milligrams of oxygen per liter (mg O_2/L) or kilograms of oxygen per cubic meter (kg O_2/m^3).
COD (Chemical Oxygen Demand): COD measures the total amount of oxygen required to chemically oxidize all organic pollutants, including biodegradable and non-biodegradable matter, in water. Its unit is milligrams of oxygen per liter (mg O_2/L) or kilograms of oxygen per cubic meter (kg O_2/m^3).

Transport Operators	Cleaning vehicles, containers, or tanks	Wastewater from cleaning operations	product residues, agrochemical residues

2.2.3. Assess the impacts of the water footprint

The water footprint assessment evaluates the potential environmental impacts associated with both water consumption and water degradation across a product's life cycle. This process relies on established methodologies to derive characterization factors (CFs) and the corresponding impact category indicators (Cabot et al., 2025; FAO, 2024) (Table 7). Depending on the study's scope, the results may be presented as a comprehensive water footprint profile encompassing all relevant impact categories, or as a focused evaluation of selected categories, termed water footprint indicators.

- **Water Scarcity (Consumptive Use)**

Water scarcity assesses the potential impact of water withdrawals on the availability of freshwater for other users in a watershed. The AWARE (Available WAter REmaining) method is applied, which calculates water availability minus human and ecosystem demand per unit area. Inventory data include water lost due to crop evapotranspiration, evaporation, discharge to other watersheds, or incorporation into products. The characterization factor expresses the relative scarcity of water in the region (m^3e/m^3), depending on location and season, with values ranging from 0.1 to 100 (Seitfudem et al., 2025).

$$WF_{\text{scarcity}} = V_{\text{water}} \times CF_{\text{AWARE}}$$

Where WF_{scarcity} is the water footprint due to scarcity (m^3e), V_{water} is the volume of water withdrawn from the watershed (m^3) and $CF_{\text{AWARE}}$is the regional characterization factor from AWARE (m^3e/m^3)

- **Freshwater Eutrophication**

Freshwater eutrophication quantifies the potential impact of phosphorus inputs on freshwater ecosystems. Excessive phosphorus can trigger algal overgrowth and oxygen depletion, disrupting aquatic life. The ReCiPe methodology, which translates emissions and resource extractions into a limited set of environmental impact scores, is applied using inventory data representing total phosphorus applied to soil or discharged into freshwater. The characterization factor (CF) varies depending on the medium and chemical form of phosphorus (Payen & Ledgard, 2019).

$$WF_{\text{freshwater\_eutro}} = P_{\text{emitted}} \times CF_P$$

Where $WF_{\text{freshwater_eutro}}$is the freshwater eutrophication impact (kg Pe), P_{emitted} is the total phosphorus applied or discharged (kg P) and CF_P is the ReCiPe phosphorus characterization factor (kg Pe/kg P).

❖ Saltwater Eutrophication

Saltwater eutrophication assesses the potential impact of nitrogen inputs on marine ecosystems. Excessive nitrogen can lead to algal blooms and oxygen depletion, disrupting aquatic life. The ReCiPe methodology is applied, with inventory data representing nitrogen applied to soil or discharged into freshwater or marine environments. The characterization factor (CF) depends on the nitrogen form and the receiving medium (Payen & Ledgard, 2019).

$$WF_{\text{saltwater\_eutro}} = N_{\text{emitted}} \times CF_N$$

Where $WF_{\text{saltwater\_eutro}}$ is saltwater eutrophication impact (kg Ne), N_{emitted} is the total nitrogen applied or discharged (kg N) and CF_N is the ReCiPe nitrogen characterization factor (kg Ne/kg N)

❖ Ecotoxicity

Ecotoxicity assesses the potential harm of chemical substances on ecosystems, including microorganisms, plants, and animals. The USEtox methodology is applied, using inventory data on the mass of active ingredients emitted to air, soil, or water. (Owsianiak et al., 2023, USEtox, 2025).

$$WF_{\text{ecotox}} = AI_{\text{emitted}} \times CF_x$$

Where WF_{ecotox} is ecotoxicity impact (CTUe, PAF·m³·day), AI_{emitted} is the mass of active ingredient emitted (kg) and CF_x is the Characterization factor for substance x given by USEtox (CTUe/kg x)

❖ Human Toxicity

Human toxicity estimates potential harm to human health from chemical emissions, including both carcinogenic and non-carcinogenic effects. The USEtox methodology is applied, using inventory data on active ingredients emitted to air, soil, or water. The CFx representing the estimated number of potential human disease cases.

$$WF_{\text{human}} = AI_{\text{emitted}} \times CF_x$$

Where WF_{human} is the human toxicity impact (CTUh), AI_{emitted} is the mass of active ingredient emitted (kg) and CF_x is the Characterization factor for substance x given by USEtox (CTUh/kg x)

Table 7. Water Footprint Impact Categories and Related Methodologies

Impact Type	Data Needed (Inventory)	Impact Indicator Units	Water Footprint / Impact Profile	Characterization Factor Units	Methodology

Consumptive Use :(Water Consumption)	Volume of water lost from the watershed	m³	Shortage / Scarcity	m³ e	AWARE = Available Water Remaining
Degradative Use: **freshwater Eutrophication**	Phosphorus applied to soil or discharged into freshwater	kg Pe	Freshwater eutrophication	kg Pe / kg P	ReCiPe methodology
Degradative Use: **Saltwater Eutrophication**	Nitrogen applied to soil or discharged into salt water	kg Ne	Saltwater eutrophication	kg Ne / kg N	ReCiPe methodology
Degradative Use: **Ecotoxicity**	Quantity of active ingredient applied	CTUe	Ecotoxicity	PAF·m³·day / kg	USEtox methodology
Degradative Use: **Human Toxicity**	Quantity of active ingredient applied	CTUh	Human toxicity	CTUh / kg	USEtox methodology

Case study: Water Footprint of the Banana Value Chain in Costa Rica

This case study examines the direct water use associated with banana production and packing activities in Costa Rica, based on the assessment presented in Chaverri et al. (2017). The analysis excludes indirect water use from inputs such as fertilizers, pesticides, packaging materials, and pallets. The water footprint was evaluated across four impact categories following LCA-based methodologies: human toxicity, freshwater ecotoxicity, freshwater eutrophication, and water scarcity.

- . **Human Toxicity (HT)**

Human toxicity evaluates the potential impact of agrochemicals applied to the banana crop (Table 8).

Table 8. Human toxicity impacts of agrochemicals used in banana production

Chemical	**Application (kg)**	**CF (CTUh/kg)**	**HT (CTUh)**
Mancozeb	15,312.87	0.000002156	0.0330
Oxamyl	2,499.82	0.000004146	0.0104
Glyphosate	568.14	0.000000160	0.00009
Bifenthrin	51.13	0.000124762	0.00638
Total			**0.04985 CTUh**

- **Freshwater Ecotoxicity (ET)**

Freshwater ecotoxicity considers the impact of agrochemicals on aquatic ecosystems (Table 9).

Table 9. Freshwater ecotoxicity impacts of agrochemicals used in banana production

Chemical	Application (kg)	CF (PAF·m³·day/kg)	ET (PAF·m³·day)
Mancozeb	15,312.87	52,559.66	804,760,559
Oxamyl	2,499.82	16,178.64	40,443,623
Glyphosate	568.14	320.79	182,254
Bifenthrin	51.13	6,578,866.63	336,394,556
Total			**1,181,780,992 PAF·m³·day**

- **Freshwater Eutrophication (Eu)**

Eutrophication assesses nutrient runoff from fertilizers and effluents from the packing plant:

-Field impact: 6,468.39 kg P × 0.053 = 342.82 kg Pe

-Packing plant impact: 0.03 kg BOD/m³ × 13,936 m³ = 4.18 kg Pe

Total Eu: 342.82 + 4.18 = 347.00 kg Pe

- **Water Scarcity (Sc)**

Water scarcity assesses the impact of water consumption relative to the availability of local water resources. At the banana farm, water consumption in the field was calculated using CropWat FAO to estimate evapotranspiration by the banana plants, resulting in a total of 2,554,974.28 m³/year.

At the packing plant, water consumption amounted to 31,444.20 m³/year, with a discharge of 13,936.00 m³/year. The total water consumption from both the field and the packing plant is:

$$2{,}554{,}974.28 + 31{,}444.20 = 2{,}586{,}418.48 \text{ m}^3\text{/year}$$

To assess water scarcity, the Available Water Remaining factor (CF_AWARE) was applied to convert the consumed volumes into water scarcity impact:

Field impact:

$$2{,}554{,}974.28 \text{ m}^3 \times 0.4 = 1{,}021{,}990 \text{ m}^3\text{e}$$

Packing plant impact:

$$31{,}444.20 \text{ m}^3 \times 0.4 = 12{,}578 \text{ m}^3\text{e}$$

The total water scarcity impact combining both the field and packing plant is:

$$1{,}021{,}990 + 12{,}578 = 1{,}034{,}568 \text{ m}^3\text{e/year}$$

3. Recommendations

The selection of an appropriate water footprint methodology should be guided by the primary objective of the study, whether focused on economic efficiency or environmental sustainability (Pfister et al., 2017; Berger et al., 2025; Mir et al., 2025) (Table 10). For assessments emphasizing economic performance, such as optimizing water use in production, minimizing operational costs, or improving resource efficiency, the first method (Hoekstra et al., 2011) is appropriate. Its volumetric approach provides clear metrics of water consumption and pollution, facilitating decision-making related to water allocation and productivity. However, it does not account for the broader environmental consequences of water use or provide precise contextualization. Conversely, for studies aimed at environmental assessment and sustainability, including potential impacts on human health, ecosystems, and regional water availability, the second method (ISO 14046, 2014) is recommended. This methodology integrates Life Cycle Assessment principles and applies characterization factors to quantify environmental impacts, offering a comprehensive footprint that supports informed decision-making on water resource management and environmental mitigation strategies. A combined approach can provide a more robust perspective by linking volumetric water use and economic considerations with the ecological and human health consequences of water consumption and pollution (FAO, 2017). Such integration enables stakeholders to design strategies that are both economically efficient and environmentally sustainable.

Table 10. Comparison of Water Footprint Methodologies: Volumetric vs. Environmental (FAO, 2017)

Aspect	Method 1: Water Footprint (Hoekstra et al., 2011)	Method 2: Water Footprint (ISO 14046, 2014)
Footprint definition	Volumetric measurement of water consumption and pollution, focusing on quantities of water used and polluted in the production of goods and services	Quantitative metrics that assess potential environmental impacts associated with water consumption and degradation across a product, process, or organization, using a Life Cycle Assessment (LCA) approach
Scope	Focuses on blue water (surface and groundwater consumption), green water (rainwater used in production), and grey water (freshwater required to assimilate pollutants). Primarily product-oriented.	Covers all significant water-related environmental impacts for products, processes, and organizations. Based on LCA principles; considers water consumption, degradation, and impacts on human health and ecosystems.
Assessment steps	1. Define objective and scope 2. develop an inventory 3. Account for water footprint (blue, green, grey) 4. Determine hotspots	1. Define objective and scope 2. Analyze water footprint inventory 3. Evaluate water footprint impact (using characterization factors) 4. Interpret results for decision-making
Results	Provides volumes of consumptive water by source type (blue, green) and freshwater required to assimilate pollutants (grey), expressed per unit of product or per unit time	Produces individual impact values or a profile of environmental impacts expressed per functional unit, allowing comparison across products, processes, or organizations

Limitations / Comments	• Does not directly measure severity of local environmental impacts • Primarily focuses on volumetric water use, with limited attention to ecological consequences or site-specific contextual factors. • Less suitable for organizational or process-level LCA • Limited integration with impact assessment methods	• Requires detailed inventory and LCA knowledge; more complex to implement • Only fully comprehensive studies including all significant environmental impacts can be called a water footprint (principle of integrality) • Focuses on environmental impacts, not economic or social values • Can be data-intensive, particularly for multi-site or multi-product assessments

4. Conclusion

The water footprint assessment of crop value chains highlights the advantages of integrating both volumetric and impact-based approaches. The volumetric method quantifies water consumption and pollution, distinguishing between blue, green, and grey water, and identifies areas of high water use while highlighting opportunities to improve economic efficiency in production systems. The ISO 14046 method complements this approach by applying Life Cycle Assessment principles to evaluate the potential environmental impacts of water use. Through characterization factors, it provides insights into effects on human health, ecosystems, and overall environmental quality, offering a comprehensive perspective across products, processes, and organizations. Together, these methodologies enable policymakers and stakeholders to design interventions that promote both environmental sustainability and resource efficiency. Limitations include gaps in primary water consumption and pollution data, reliance on estimates, and the exclusion of indirect water use from inputs such as fertilizers, packaging, and energy. Despite these challenges, both methods are adaptable to various agricultural systems by adjusting system boundaries, functional units, production stages, and impact categories. Choosing the most suitable method depends on the assessment objectives and the availability of reliable data, providing a robust framework for fostering sustainable, resilient, and resource-efficient agri-food systems in Tunisia.

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References

Arrien, M. M., Aldaya, M. M., & Rodríguez, C. I. (2025). Livestock and water resources: A comparative study of water footprint in different farming systems. *Sustainability, 17*(5), 2251. https://doi.org/10.3390/su17052251

Berger, M., Gerbens-Leenes, W., Karandish, F., Aldaya, M. M., Boulay, A.-M., Hogeboom, R. J., … Wöhler, L. (2025). Complementary strengths of water footprint and life cycle assessments in analyzing global freshwater appropriation and its local impacts: Recommendations from an interdisciplinary discussion series. *Ecological Indicators, 174,* 113458. https://doi.org/10.1016/j.ecolind.2025.113458

Cabot, M. I., Lado, J., & Sanjuán, N. (2025). Peeling the orange: Delving into life cycle indicators for water footprint, ecosystem services, and biodiversity for orange cultivation in Uruguay. *Sustainable Production and Consumption, 54,* 261–273. https://doi.org/10.1016/j.spc.2025.01.015

Chebil, A., Frija, A., Makhlouf, M., Thabet, C., & Jebari, S. (2019). Effects of water scarcity on the performances of the agricultural sector and adaptation strategies in Tunisia. *IntechOpen.* https://doi.org/10.5772/intechopen.83568

Chouchane, H., Hoekstra, A. Y., Krol, M. S., & Mekonnen, M. M. (2013). Water footprint of Tunisia from an economic perspective. Value of Water Research Report Series No. 61, UNESCO-IHE, Delft, The Netherlands.

FAO. (2003). *Technical conversion factors for agricultural commodities.* Food and Agriculture Organization. http://www.fao.org/fileadmin/templates/ess/documents/methodology/tcf.pdf

FAO. (2017). *Banana cultivation and water management* (1st ed.). Rome, Italy: FAO. https://openknowledge.fao.org/handle/20.500.14283/i6914en

FAO. (2024). *Measuring carbon and water footprints in pineapple value chains.* Rome. https://doi.org/10.4060/cd1688en

Gerbens-Leenes, W., Berger, M., & Allan, J. A. (2021). Water footprint and life cycle assessment: The complementary strengths of analyzing global freshwater appropriation and resulting local impacts. *Water, 13*(6), 803. https://doi.org/10.3390/w13060803

Gargouri, B., Ben Brahim, S., Marrakchi, F., Ben Rouina, B., Kujawski, W., & Bouaziz, M. (2022). Impact of wastewater spreading on properties of Tunisian soil under arid climate. *Sustainability, 14*(6), 3177. https://doi.org/10.3390/su14063177

Hoekstra, A. Y., & Chapagain, A. K. (2008). *Globalization of water: Sharing the planet's freshwater resources.* Blackwell Publishing.

Hoekstra, A. Y., Chapagain, A. K., Aldaya, M. M., & Mekonnen, M. (2011). *The water footprint assessment manual: Setting the global standard.* Daugherty Water for Food Global Institute: Faculty Publications, 77. https://digitalcommons.unl.edu/wffdocs/77

Hoekstra, A. Y. (Ed.). (2003). *Virtual water trade.* Proceedings of the International Expert Meeting on Virtual Water Trade, 12–13 December 2002, Delft. Value of Water Research Report Series No. 12, UNESCO-IHE.

ISO. (2014). *International standard 14046: Environmental management — Water footprint: Principles, requirements and guidelines.* ISO.

Mohlotsane, M. P., Owusu-Sekyere, E., Jordaan, H., Barnard, J. H., & Van Rensburg, L. D. (2018). Water footprint accounting along the wheat-bread value chain: Implications for sustainable and productive water use benchmarks. *Water, 10*(9), 1167. https://doi.org/10.3390/w10091167

Mir, B. A., Nurdiawati, A., & Al-Ghamdi, S. G. (2025). Assessing the environmental impact of freshwater use in LCA: Established practices and current methods. *Environmental Science: Water Research & Technology, 11,* 196–221. https://doi.org/10.1039/D4EW00641K

Owsianiak, M., Hauschild, M. Z., Posthuma, L., Saouter, E., Vijver, M. G., Backhaus, T., … Fantke, P. (2023). Ecotoxicity characterization of chemicals: Global recommendations and implementation in USEtox. *Chemosphere, 310,* 136807. https://doi.org/10.1016/j.chemosphere.2022.136807

Osorio-Tejada, J. L., Varón-Hoyos, M., & Morales-Pinzón, T. (2022). Comprehensive water footprint of a university campus in Colombia: Impact of wastewater treatment modeling. *Water, Air, and Soil Pollution, 233,* 174. https://doi.org/10.1007/s11270-022-05644-3

Payen, S., & Ledgard, S. F. (2019). Application of eutrophication potential indicators in a case study catchment in New Zealand. *Our Land & Water / LCAFood Conference Proceedings.* https://ourlandandwater.nz/wp-content/uploads/2019/03/EPF_Full-Paper-Payen-and-Ledgard-FINAL-VERSION-LCAFood-Conf-Dublin.pdf

Pfister, S., Boulay, A.-M., Berger, M., Hadjikakou, M., Motoshita, M., Hess, T., … Henderson, A. (2017). Understanding the LCA and ISO water footprint: A response to Hoekstra (2016) "A critique on the water-scarcity weighted water footprint in LCA." *Ecological Indicators, 72,* 352–359. https://doi.org/10.1016/j.ecolind.2016.07.043

Seitfudem, G., Berger, M., Schmied, H. M., & Boulay, A.-M. (2025). The updated and improved method for water scarcity impact assessment in LCA, AWARE2.0. *Journal of Industrial Ecology, 29,* 891–907. https://doi.org/10.1111/jiec.70023

Shahnum, S., & Shah, M. S. (2024). Assessing the impact of agriculture value chains on food and water environments in Meerut District, India. *Discover Sustainability, 5,* 395. https://doi.org/10.1007/s43621-024-00561-3

Souaissi, A., Mtimet, N., Thabet, C., Stambouli, T., & Chebil, A. (2019). Impact of food consumption on water footprint and food security in Tunisia. *Food Security*. https://doi.org/10.1007/s12571-019-00966-3

Soula, R., Chebil, A., Majdoub, R., Kahil, T., & Albiac, J. (2025). Utilisation des instruments économiques pour réduire l'épuisement des eaux souterraines dans le contexte du changement climatique: Cas de l'aquifère de Mahdia-Ksour Essef en Tunisie. *Cahiers Agricultures, 34,* Article 7. https://doi.org/10.1051/cagri/2025003

Soula, R., Chebil, A., McCann, L., & Majdoub, R. (2021). Water scarcity in the Mahdia region of Tunisia: Are improved water policies needed? *Groundwater for Sustainable Development, 12,* 100510. https://doi.org/10.1016/j.gsd.2020.100510

Usetox. (2025). What are the USEtox user interfaces and how do they work? https://usetox.org/model/download

Vallejo Chaverri, A. L., Vallejo Solís, M. Á., Nájera Fernández, J., & Garnier Zamora, L. A. (2017). *Methodological guide to reduce carbon and water footprints in banana plantations. ACCIÓN Clima II Project.* FAO. https://openknowledge.fao.org/server/api/core/bitstreams/dc26316c-f8a8-42dc-8d39-5c5bf64161ea/content

Water Footprint Assessment Tool (WFAT)(2025). Total water footprint accounting by country. https://www.waterfootprintassessmenttool.org/countries/~TUN/accounting/map/total