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

Scoping Study on Strategic Value Chains, Food Loss and Waste and Water Productivity in Tunisia

Deliverables Report:

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

Boubaker Dhehibi[1], Rania Soula[1], Bezaiet Dessalegn[2], Asma Souissi[3], Mohamed Zied Dhraief[4]

[1]Social, Economic, and Policy Research Team (SEP-RASP), International Center for Agricultural Research in the Dry Areas (ICARDA), Ariana, Tunisia (b.dhehibi@cgiar.org; r.soula@cgiar.org)
[2]Social, Economic, and Policy Research Team (SEP-RASP), International Center for Agricultural Research in the Dry Areas (ICARDA), Cairo, Egypt (b.dessalegn@cgiar.org)
[3]Higher School of Agriculture of Mograne, University of Carthage, Zaghouan, Tunisia (asmasouissi.fr@gmail.com)
[4]Department of Agricultural Economics, National research Agronomic of Tunisia (INRAT), Ariana, Tunisia (medzied.dhraief@inrat.ucar.tn)

January 2026

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List of Acronyms

AHP: Analytic Hierarchy Process

ARDII-Tounes: Agricultural Risk Diagnosis, Impact and Investment (Tunisia programme)

CWP: Crop Water Productivity

CWUModel: Crop Water Use Model

DEA: Data Envelopment Analysis

EWP: Economic Water Productivity

ET: Evapotranspiration

FAO: Food and Agriculture Organization of the United Nations

FL: Food Loss

FLW: Food Loss and Waste

FW: Food Waste

GDP: Gross Domestic Product

GIZ: German Agency for International Cooperation

HLPE: High-Level Panel of Experts on Food Security and Nutrition

ICARDA: International Center for Agricultural Research in the Dry Areas

IFAD: International Fund for Agricultural Development

IRM: Iterative Relational Mapping

ISO: International Organization for Standardization

IWP: Irrigation Water Productivity

LCA: Life Cycle Assessment

LCI: Life Cycle Inventory

LCIA: Life Cycle Impact Assessment

MACTOR: Matrix of Alliances and Conflicts

MCDA: Multi-Criteria Decision Analysis

NWP: Nutritional Water Productivity

NDVI: Normalized Difference Vegetation Index

NFLWF: Nutritional Food Loss and Waste Footprint

NSCC: National Strategy for Climate Change Adaptation

PAW: Productivity of Applied Water

PRA: Participatory Rural Appraisal

SDG: Sustainable Development Goal

SWOT: Strengths, Weaknesses, Opportunities and Threats

TFSS: Tunisia Food Security Strategy

UNEP: United Nations Environment Programme

UNFCCC: United Nations Framework Convention on Climate Change

USDA: United States Department of Agriculture

VCA: Value Chain Analysis

WF: Water Footprint

WFV: Water Footprint of Value

WUE: Water Use Efficiency

WP: Water Productivity

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Key messages

Executive Summary

This scoping study investigates the critical intersections between agricultural value chains, food loss and waste (FLW), and water productivity within the context of Tunisia's severe water scarcity and climate vulnerability. Against a backdrop of renewable water resources falling below 500 m^3 per capita and projected rainfall declines, the research synthesizes academic and grey literature to align agricultural development with environmental constraints. The analytical framework integrates global value chain theory, sustainable FLW concepts, and water footprint assessment methodologies, focusing specifically on strategic sectors such as olive oil, dates, cereals, and dairy. By reviewing existing assessment methods—ranging from SWOT and MACTOR stakeholder analyses to Life Cycle Assessments (LCA) and volumetric water accounting—the study evaluates how production, processing, and consumption behaviours impact resource efficiency across the country's primary agricultural systems.

The analysis reveals deep structural interdependencies where water productivity and food loss are mutually reinforcing challenges. The findings highlight that crop production accounts for the vast majority of Tunisia's national water footprint, with blue water consumption in irrigated areas frequently exceeding sustainable renewable limits. While technologies like drip irrigation and two-phase olive oil extraction offer pathways to improved physical water productivity, the report identifies a "sustainability paradox" where private irrigation efficiency increases individual farm profitability but drives collective aquifer depletion. Furthermore, the study redefines food loss and waste in the Tunisian context to include not only physical post-harvest losses caused by aging infrastructure but also systemic misalignments between production and market requirements which result in the significant wastage of embedded blue and green water.

Despite the economic importance of these strategic chains, the study identifies critical knowledge gaps, including inconsistent FLW quantification methods and a lack of granular, region-specific water productivity data for non-export crops. Current research tends to treat value chains, water use, and waste in isolation, failing to capture the cascade effects where upstream production inefficiencies lead to downstream resource waste. Consequently, the study emphasizes the urgent need for integrated, multi-scale analytical frameworks that combine physical water metrics with economic value assessments. It suggests that future strategies must prioritize institutional coordination between production and processing nodes, standardize measurement protocols, and leverage virtual water concepts to reconcile national food security goals with the arid-zone limitations.

Keywords

Water scarcity; climate vulnerability; agricultural value chains; food loss and waste; water productivity; olive oil; dates; cereals; dairy; irrigation efficiency; post-harvest losses; Life Cycle Assessment; stakeholder analysis; SWOT; MACTOR; water footprint accounting; virtual water, Tunisia

Highlights

• Tunisia’s agricultural value chains operate under extreme water scarcity, with crop production dominating the national water footprint and frequently exceeding sustainable blue water limits.

• Water productivity and food loss and waste are mutually reinforcing challenges, where inefficiencies across production, processing, and markets lead to significant losses of embedded water.

• Technological efficiency gains (e.g. drip irrigation, modern olive oil processing) improve farm-level productivity but create a sustainability paradox by accelerating collective groundwater depletion.

• Food loss and waste in Tunisia extend beyond physical losses to include systemic mismatches between production and market demand, resulting in wasted economic and water value.

• Addressing these challenges requires integrated, multi-scale analytical frameworks that align water footprint metrics, economic value, and institutional coordination to balance food security with arid-zone constraints.

1. Introduction

1.1. Background and Context

Agriculture remains a major pillar of Tunisia's economy, contributing around 9–10% of GDP over the last decade and providing employment for 16% of the active population (Thabet et al. 2024). Yet this sector is increasingly constrained by severe water scarcity, accelerating climate change and long-standing structural and policy distortions (Verner et al. 2018). Tunisia is already among the most water-stressed countries globally, with renewable resources below 500 m³ per capita per year, and projections indicate a 10–35% decline in rainfall and temperature increases of up to 2.9°C by the end of the century (Verner et al. 2018; Dhraief et al. 2019; Frija et al. 2021; Ouessar et al. 2021).

These climatic and hydrological constraints translate into shrinking irrigated areas, greater dependence on low-productivity rainfed systems, and a consequent deterioration of farm incomes and rural employment opportunities (Chebil et al. 2019; Besser et al. 2021). In response to reduced surface water availability, farmers have intensified groundwater pumping, while irrigation schemes often remain inefficient, accelerating aquifer depletion, land degradation, salinization and loss of soil fertility (Schütze et al. 2025). This context contributes to substantial productivity gaps: technical inefficiencies, combined with binding water constraints, depress yields across several key crops (Chebil et al. 2019).

At the same time, Tunisian agriculture is increasingly exposed to international market dynamics. Structural weaknesses in competitiveness and productivity, together with a growing reliance on imported food staples and animal feed, heighten the sector's vulnerability to external price shocks and trade liberalization pressures (Ouertani et al. 2016; Taghouti et al. 2017).

Addressing these challenges requires integrated water management, climate-smart practices, policy reforms, and targeted support for vulnerable groups to ensure food security and sustainable rural development.

Building on this challenging context, strategic agricultural value chains in Tunisia can be understood as the sequence of actors and activities that transform water-dependent crops from input supply and on-farm production through processing, distribution and retail to final consumption, with particular attention to those chains that are most critical for food security, rural employment and trade. Along these value chains, substantial food loss and waste (FLW) occur during harvesting, storage, processing, marketing and consumption, which not only erode incomes and nutrition but also embody large volumes of scarce blue and green water already used in production. At the global level, nearly one-third of all food produced is lost or wasted, implying massive, avoidable losses of water, land and energy and directly undermining food security and the sustainable use of water resources (Shafiee-Jood & Cai 2016; Wani et al. 2023; Sewell 2024; Gatto & Chepeliev 2024). In Tunisia, the water footprint of food consumption has increased by about 31% in recent decades, largely driven by dietary shifts toward more water-intensive animal products, which amplifies pressure on already limited water resources (Souissi et al. 2019). Against this backdrop, reducing FLW and analysing water productivity and water footprints within priority value chains offers a coherent framework for this scoping study to identify where Tunisia can generate more value and less loss per unit of water, thereby aligning agricultural development with the country's acute water-scarcity and climate constraints.

1.2. Objectives of the Scoping Study

This scoping study is designed to clarify how value chains, food loss and waste, and water use metrics can jointly inform more sustainable agricultural strategies in Tunisia, guided by four specific objectives:

- To review and compare existing methods for assessing food loss and waste and agricultural water productivity, and identify those most relevant for Tunisian conditions.
- To analyse how value chains, food loss and waste, and water productivity interact in Tunisia, with a focus on strategic crops and key stages along the chain.
- To evaluate the applicability, strengths and limitations of the Water Footprint approach for Tunisian agricultural value chains and synthesize the main findings from its use.
- To identify critical knowledge gaps, methodological needs and priority areas for future research, policy action and investment.

1.3. Scope of the Study

Geographically, this study focuses exclusively on Tunisia, with particular attention to water-stressed agricultural areas. It is limited to strategic agricultural value chains and their interactions with food loss and waste, agricultural water productivity and the Water Footprint concept. Methodologically, it relies primarily on a structured review of academic and grey literature and on conceptual analysis, synthesizing existing approaches and empirical findings.

2. Analytical Framework

The analytical framework for this scoping study is grounded in established theoretical perspectives on value chains, resource use and sustainability. It first draws on global and sustainable food value-chain theory, including Porter's value-chain concept and subsequent work on global (Assche 2019; Antràs 2019) and sustainable food value chains (Ikerd 2011; Wollni et al. 2025), to define value-chain functions and to set criteria for identifying "strategic" agricultural value chains in Tunisia in terms of economic, social and environmental relevance. Building on this foundation, the framework integrates sustainability-oriented FLW concepts that view losses and waste along the chain through environmental, economic and social lenses, as in recent holistic FLW assessment frameworks. Finally, it mobilizes water-productivity theory, which links physical or economic output to water use, together with the Water Footprint Assessment framework that distinguishes green, blue and grey water footprints, to structure the review of methods used to quantify water use and embedded water along these value chains.

2.1. Definition and Importance of Value Chains Analysis

Value chain analysis systematically evaluates the sequence of activities involved in producing and delivering a product or service, identifying how each step contributes to overall value creation. Introduced by Michael Porter in 1985, it dissects a firm's operations into (i) primary activities such as inbound logistics, operations, outbound logistics, marketing/sales, services, and (ii) support activities (procurement, technology development, human resource management, firm infrastructure), aiming to pinpoint sources of competitive advantage through cost reduction or differentiation. Value chain analysis serves as a rigorous framework for dissecting economic systems, particularly in agriculture and rural development, to quantify value addition at each node—from production to consumption (Rich et al. 2011). It employs quantitative metrics like cost-

benefit ratios, productivity indices, and econometric models to assess efficiency, while qualitative methods such as stakeholder mapping reveal governance structures and power dynamics (Faße, et al. 2009). This analysis is crucial for optimizing resource allocation in resource-constrained environments, such as semi-arid agricultural systems, by highlighting bottlenecks in water use or food loss. It informs policy design, enhances farmer resilience through targeted interventions, and supports sustainable development goals by linking micro-level farm activities to macro-level market outcomes (Lutta et al. 2024).

2.2. Methodological Approaches in Tunisian Agriculture Value Chain Analysis

Table 1 summarizes key methodological approaches of value chain analysis employed across various recent studies that contribute to understanding agricultural development strategies in Tunisia through four distinct but complementary mechanisms:

- **Structured analytical frameworks**

The Structured analytical frameworks such as SWOT and MACTOR analyses enable systematic identification of chain weaknesses including insufficient transparency, informal sector dominance, and coordination failures. According to Blom-Zandstra et al. (2018), the potato sector SWOT analysis enabled identification of specific weaknesses including insufficient transparency, distrust, lack of long-term perspective, and parallel illegal chains, while simultaneously highlighting opportunities for mechanization, storage infrastructure, and farmer training. Clodoveo et al. (2021) performed a SWOT analysis on the Tunisian olive oil sector, encompassing the full chain from olive growing through packaging and marketing.

MACTOR is a strategic stakeholder analysis method that quantifies alliances, conflicts, and power relations among actors around a shared set of objectives. It uses matrices where each actor's position (support/opposition) on each objective is scored, then derives indicators of influence, convergence/divergence, and potential coalitions (Fetoui et al. 2020a). In value chain analysis, MACTOR helps reveal power asymmetries, likely alliances, and conflicts among chain actors (farmers, traders, processors, institutions), guiding upgrading strategies and governance arrangements (Arcade et al. 2014). The MACTOR approach applied to the olive oil value chain in Medenine (Tunisia) specifically established linkages among chain operators, revealing the essential role of public-private-civil society partnerships (Fetoui et al. 2020b).

- **Multi-stakeholder approaches**

These approaches emphasize collaboration across the chain to identify bottlenecks, power imbalances, and opportunities, often using tools like participatory rural appraisal (PRA), stakeholder workshops, and surveys. They shift from linear, top-down models to inclusive, systemic analysis that captures real-world interactions and behaviours (Ramirez 2001; Brouwer et al. 2012). Multi-stakeholder approaches yield precise quantitative insights into market dynamics and stakeholder behaviours. For instance, a goat farming study engaged 196 participants across the value chain and revealed that 92% of butchers prefer fattened animals, while only 16% of farmers engage in fattening practices. It also documented a 72% consumer purchasing rate for goat meat. This level of specificity enables targeted interventions to address documented market failures (Day et al. 2025).

- **Qualitative expert-driven approaches**

Qualitative expert-driven approaches in Value Chain Analysis (VCA) primarily involve structured expert elicitation methods to map and analyse supply chain relationships and dynamics. The Key approaches include:

1. Expert panel consultations: an approach involving experts using methods like online questionnaires, interviews, Delphi technique and Failure Mode and Effect Analysis (FMEA) (Marvin et al. 2020).
2. Iterative Relational Mapping (IRM): an approach developed by Howieson et al. (2016) focusing on strategic understanding through expert interactions, revealing the importance of formal and informal behaviours in value chain relationships. IRM maps are drawn iteratively through expert interviews, starting with simple sketches of value chain actors and their links, then refining based on feedback to include both formal contracts and informal influences like trust or habits.
3. Comparative Expert Analysis: Kim et al. (2018) showed that expert insights remain crucial for validating analytical results, despite emerging data-driven techniques. The strength of these approaches lies in their ability to capture nuanced, contextual insights that quantitative methods might miss, though they can be subjective and resource-intensive.

These qualitative approaches reveal institutional and governance challenges often overlooked by quantitative analyses. A date sector study of support organizations found that they lack a shared vision on export-strengthening priorities, representing a coordination failure beyond the scope of structured analytical methods (Rouached et al. 2023). Likewise, expert interviews in another date value chain analysis uncovered a "two-speed" chain structure and the promise of Social and Solidarity Economy models (Boughzala et al. 2022).

- **Production-focused analyses**

These analyses usually target the upstream production stage, such as crop cultivation or livestock rearing, to pinpoint inefficiencies like low yields, high input costs, or practices that hinder output and quality before downstream processing. Analyses often use methods like Live Cycle Assessment (LCA), Data Envelopment Analysis (DEA) and stochastic frontier models to assess technical, allocative, and economic efficiency at the farm or production stage, identifying sources of low yields, high input costs, and suboptimal practices in both crop and livestock systems (Naseer et al. 2019; Li et al. 2024). The examined farm-level metrics include seed and fertilizer use, labour efficiency, and technology adoption, often through surveys or cost accounting to measure inputs against outputs like yield per hectare. Unlike holistic VCA, these approaches prioritize production optimization as the foundational link, integrating with chain mapping to ensure gains translate to market viability.

In Tunisia, several studies have highlighted major production inefficiencies, including the use of poor-quality inputs (seeds, fertilizers, pesticides), inadequate irrigation, limited access to extension services, and farm management practices, all of which reduce yields and product quality before processing (Ben Abdallah et al. 2022; Dhehibi et al. 2025; Hammami et al. 2025). According to Anvari et al. (2024), production-focused analyses provide technical insights into resource efficiency and sustainability by quantifying underutilized biomass streams. Olive tree pruning residues were estimated at 1.43–2 t/ha/year and date palm fruit residues at 7.2–29.5 t/ha/year, indicating significant but underexploited development opportunities. These analyses also show that only about 10–12% of olive oil production waste is currently used for bioenergy, despite its considerable potential for energy recovery and circular use.

Table 1. Illustrative applications of value chain analysis approaches in Tunisian agriculture

Study	Value Chain Focus	Key Stakeholders Engaged	Analytical Framework	Primary Methodology	Data Collection Methods
Blom-Zandstra et al. 2018	Potato	Smallholders, private sector, experts	SWOT analysis	Multi-stakeholder approach	Survey, interviews during field mission
Rouached et al. 2023	Dates	Public support organizations	Exploratory and qualitative	Exploratory qualitative approach	Semi-structured interviews
Fetoui et al. 2020b	Olive oil	Public-private-civil society partnerships	MACTOR	MACTOR approach	Semi-structured interviews, participatory workshops
Boughzala et al. 2022	Dates	National and international experts	Qualitative research	Qualitative methodology	Semi-directive interviews, government data analysis
Day et al. 2025	Goat farming	80 farmers, 3 veterinarians, 13 butchers, 100 consumers	Transferable framework	Multi-stakeholder approach	Focus groups, semi-structured questionnaires, direct observations
Clodoveo et al. 2021	Olive oil	Experts, actors in olive oil sector	SWOT analysis	Quanti-qualitative analysis	Semi-structured interviews, workshops

Value chain analysis methodologies contribute to understanding Tunisian agricultural development by: (1) systematically mapping chain structure and identifying coordination failures; (2) quantifying stakeholder behaviours and market dynamics; (3) revealing institutional and governance challenges; (4) identifying untapped opportunities for sustainability and value addition; and (5) generating context-specific, actionable recommendations that account for Tunisia's particular environmental, economic, and social conditions.

2.3. Strategic Value Chains in Tunisian Agriculture

Tunisia's policies and programs addressing food security, climate adaptation, and resource management directly target strategic crops and sectors, defined by criteria like contributions to food security (staple consumption), export earnings, employment, regional development, and water use efficiency (Chebil et al. 2019; Frija et al. 2021; Elfkih et al. 2023). National and international institutions, including FAO, IFAD, ICARDA, and GIZ, prioritize tree crops (especially olives and dates), cereals (durum wheat and barley), and livestock (red meat and milk) due to their dominance in cultivated area, value added, rural incomes, and roles in resilience amid drought and market volatility.

The Tunisia's Food Security Strategy (TFSS) aligns with these priorities by pursuing self-sufficiency in cereals, red meat, poultry, and milk, while modernizing strategic sectors like cereals, olives, dates, and citrus to enhance competitiveness, stabilize farmer incomes through price incentives for grains and dairy, and empower vulnerable smallholders (Ouessar et al. 2021).

National Climate strategies also reinforce this focus. The National Strategy for Adapting to Climate Change (NSCC) and its agriculture-specific counterpart promote drought-resilient practices, such as breeding water-stress and salt-tolerant varieties suited to olive, dates, and cereals, alongside agroecology and biodiversity preservation. Water management initiatives, including the National Water Saving Program and non-conventional resource mobilization (e.g., desalination), address the high-water demands of these crops, complemented by desertification controls and land rehabilitation dating to the 1960s. Livestock intensification via imported grains further stabilizes red meat and dairy production. Ratified international agreements (UNFCCC 1993, Kyoto 2002, Paris 2016) integrate these efforts into global resilience frameworks, forming a cohesive "shield" against shocks and a "ladder" for rural economic stability (Ouessar et al. 2021).

2.3.1 Identification of Strategic Crops and Sectors

Existing value chain and sector studies in Tunisia focus heavily on olive oil, dates, dairy, red meat, cereals, and fruit/tree crops, examining competitiveness, quality, and inclusiveness. These works typically operationalize “strategic” status by combining quantitative indicators (production value, export share, employment) with qualitative judgments on regional importance and vulnerability, especially in lagging regions such as the North-West and South (Dey et al. 2025; Mejri et al. 2025). This framing aligns strategic crop selection with broader agricultural development goals, including rural poverty reduction and sustainable resource management (Verner et al. 2018; Oe & Yamaoka 2023).

2.3.2. Approaches for Value Chain Selection and Prioritization

Global and regional literature on value chain selection in agriculture relies heavily on multi-criteria decision analysis (MCDA), stakeholder consultation, and economic impact assessments to rank candidate chains. MCDA frameworks structure decisions around sets of criteria—typically economic (value added, growth potential), social (employment, poverty impact, gender inclusion), environmental (water use, land degradation), and institutional (organization, policy support)—with weights derived from expert or stakeholder judgments (Jellali et al. 2021). Methods such as the Analytical Hierarchy Process (AHP), scoring and ranking matrices, or simple weighted indices are frequently used to compare crops or value chains transparently (Abdallah et al. 2024).

In Tunisia, recent initiatives have adapted these approaches through participatory workshops and living labs that ask local actors to prioritize value chains based on economic, social, and environmental criteria. For example, a participatory agroecological assessment in Siliana and Kef used stakeholder scoring to identify olive oil, as priority chain, after initial screening of cereals, olives, and small ruminants (Souissi et al. 2024; Mejri et al. 2025). Donor programmes (e.g., IFAD country strategies, GIZ/ICARDA projects, PARM- ARDII-Tounes) similarly combine quantitative diagnostics (production value, risk exposure) with structured stakeholder dialogue to select and sequence value chains for investment, ensuring that prioritization reflects both national strategies and local development needs.

3. Value Chains, Food Loss and Waste, and Water Productivity in Tunisia

3.1. Food Loss and Waste in Agricultural Value Chains

Most frameworks distinguish food loss (FL) from food waste (FW) and use Food Loss and Waste (FLW) for their total. FAO (2014) and sustainable development goals (SDG 12.3) define FL as a decrease in the quantity or quality of food occurring from production, post-harvest and processing up to, but not including, the retail stage, and attributable to the actions or decisions of food suppliers. FW, in contrast, refers to a decrease in quantity or quality resulting from the actions or decisions of retailers, food service operators and consumers. FLW thus covers all such reductions affecting food initially intended for human consumption (Boiteau & Pingali 2023).

Several institutional frameworks adopt closely related distinctions. The High-Level Panel of Experts on Food Security and Nutrition (HLPE) defines food loss as occurring before the consumer level and food waste as occurring at the consumer level. The United States Department of Agriculture (USDA considers food waste to be the edible portion of food loss that ultimately goes unconsumed (Ishangulyyev et al. 2019). Finally, many authors also distinguish quantitative FLW, referring to losses in mass or volume, from qualitative FLW, referring to the loss of nutritional, safety or sensory quality (Delgado et al. 2020; Nicastro & Carillo 2021; De Boni et al. 2022). In other words, FLW describes any reduction in the edible quantity or quality of food intended for human consumption, from the moment it is ready for harvest or slaughter until it is eaten. “Food loss” is mainly upstream (farm to processing), while “food waste” is mainly downstream (retail to consumer), but together they span the entire agricultural value chain from farm to fork (Table 2).

Table 2. Food loss and waste across all stages of the food supply chain

Chain stage: farm to fork	Typical examples of FLW	FL vs FW	Citations
1. Primary production (on-farm, pre-/at harvest)	Unharvested crops, damage by pests/weather, livestock mortality	Food loss	Vilariño et al. 2017 Ishangulyyev et al. 2019 Delgado et al. 2020 De Boni et al. 2022
2. Post-harvest handling & storage	Spillage, spoilage in storage, poor drying/cooling	Food loss	Vilariño et al. 2017 Ishangulyyev et al. 2019 De Boni et al. 2022
3. Processing & packaging	Trimming, quality downgrades, process losses	Food loss	Vilariño et al. 2017 Delgado et al. 2020 Nicastro & Carillo 2021
4. Distribution / wholesale / transport	Damage, temperature breaks, rejected loads	Food loss	Vilariño et al. 2017 Ishangulyyev et al. 2019
5. Retail (shops, markets)	Over-ordering, expired stock, cosmetic rejection	Food waste	Vilariño et al. 2017 Ishangulyyev et al. 2019 Nicastro & Carillo 2021 De Boni et al. 2022
6. Food service (restaurants, canteens)	Plate waste, buffet leftovers, prep waste	Food waste	Nicastro & Carillo 2021
7. Households (consumption)	Food discarded uneaten, over-preparation	Food waste	Vilariño et al. 2017 Ishangulyyev et al. 2019 Nicastro & Carillo 2021

3.1.1. Global and Regional FLW Trends and Impacts.

Around one-third of produced food is lost or wasted each year, representing 1.3 billion tons, and 24% of global food calories (614 kcal/cap/day) (Dou 2024). New global estimates for 121 countries show FLW rose by 25% between 2004–2014, with strongest increases in Sub-Saharan Africa and Southeast Asia (Gatto & Chepeliev 2024). In 2022, an estimated 13% of all food produced globally was lost along the supply chain, and a further 19% of the food available to consumers was wasted at the retail, food service and household levels. The largest shares of food loss and waste are observed for fruits and vegetables (45%), followed by fish and seafood (35%), cereals (30%), dairy products (20%), and meat and poultry (20%) (UNEP, 2024). Per-capita household waste tends to increase with GDP, so high-income countries waste more at consumer level, while developing countries lose more food upstream (Baykoca & Yılmaz 2025).

Globally, food loss and waste (FLW) exert major environmental, climatic, food security and economic impacts. FLW use about 198 million hectares of cropland (20% of global cropland) and an estimated 173–250 km^3 of water each year, in addition to large quantities of fertilizers and energy, while per-capita FLW-related greenhouse gas emissions increased by about 44% between 1961 and 2011 (Ishangulyyev et al. 2019). When landfilled, wasted food generates methane, and overall FLW-related emissions are comparable to those of some large emitting countries (Xue et al. 2024). By removing edible food from the system, FLW directly reduce the food available for human consumption, and various estimates suggest that the quantities lost or wasted would be sufficient, in theory, to feed hundreds of millions of people (Mokrane et al. 2023). The associated economic damage is also substantial, amounting to hundreds of billions of US dollars every year through lost product value, inefficient use of inputs and additional waste management costs (Vilariño et al. 2017; Spang et al. 2019).

In the Arab world, per-capita food loss and waste (FLW) can exceed 210 kg per year, while applied and quantitative empirical studies remain relatively scarce (Abiad & Meho 2018). In Tunisia, household food waste was estimated at around 112 kg per capita per year in 2017, corresponding to about 5% of household food expenditure, or approximately 197 million US dollars annually (Jribi et al. 2020). Tunisian research indicates that household food waste is widespread in normal times but that crisis periods, such as the COVID-19 lockdown, temporarily reduced waste through improved meal planning and greater use of leftovers (Jribi et al. 2020). In parallel, a dedicated project targeting FLW reduction in cereals and dairy value chains in Tunisia documents significant losses along these chains and emphasizes the contribution of FLW reduction to food security and rural livelihoods (FAO 2019).

3.1.2. Main Methods for Assessing FLW

Food loss and waste can be quantified using several complementary approaches, each with specific strengths and limitations. Direct measurement methods, such as waste audits, weighing, and composition analysis conducted at farms, processing plants, retail outlets, and households, provide highly accurate and detailed data, but they are resource-intensive and usually limited to small or local scales (Hoehn et al. 2022). In contrast, surveys, food diaries, and interviews rely on self-reported information from households or businesses; these methods are less costly and easier to implement over large samples, yet they tend to underestimate waste because of recall bias and social desirability effects (Amicarelli & Bux 2020; Hoehn et al. 2022).

At broader scales, secondary-data modelling approaches use sources such as FAO Food Balance Sheets combined with loss coefficients to generate national or global estimates (Fabi et al. 2020;

Gatto & Chepeliev 2024). While these models enable cross-country comparisons and long-term trend analysis, they suffer from high uncertainty, assumptions that are not always transparent, and particularly weak reliability in low- and middle-income countries where primary data are scarce. More recently, integrated accounting frameworks have emerged that combine physical material flow analysis with economic or nutritional valuation. Examples include indices like the Nutritional Food Losses and Waste Footprint (NFLWF) (Garcia-Herrero et al. 2018), and multi-criteria sustainability assessments, which allow researchers and policymakers to evaluate not only the quantity of food lost or wasted but also its nutritional, economic, and environmental significance, and to compare the performance of different prevention or reduction strategies (Goossens et al. 2019; Muñoz-Torres et al. 2025).

Table 3 outlines key assessment objectives for FLW alongside the most relevant quantification methods, their justification adapted to Tunisian semi-arid conditions and strategic chains (e.g., cereals, olives), and supporting citations.

Table 3. Key FLW assessment methods and relevance to the Tunisian context

Objective	Most relevant methods	Justification	Citations
National baseline	FAO balance-sheet based + country-specific coefficients	Comparable with SDG 12.3; must adjust generic factors to Tunisian chains	Hoehn et al. 2022 Wani et al. 2023 Gatto & Chepeliev 2024
Priority hotspots	Targeted direct measurements along key chains (cereals, olives, fruit/veg)	Identifies Tunisian-specific losses in semi-arid, infrastructure-constrained systems	Garcia-Herrero et al. 2018 Amicarelli & Bux 2020 Hoehn et al. 2022
Policy design	FLW + economic/nutritional indices (e.g., NFLWF)	Links losses to food security and health; fits Mediterranean context	Garcia-Herrero et al. 2018 Allen et al. 2019 Gatto & Chepeliev 2024

3.1.3. Drivers of FLW Along Tunisian Value Chains

FLW in Tunisia is driven by distinct but interconnected factors along agricultural value chains.

- **Upstream: production and post-harvest**

In Tunisia's wheat value chain, losses are closely linked to harvesting technology and farm scale: small farms often rely on older, poorly adjusted harvesters that generate higher grain losses than the better-equipped large farms (Anríquez et al. 2020). Despite these physical losses, many farmers perceive limited economic incentive to invest in improved machinery or practices at current scales and price levels (Anríquez et al. 2020). Broader regional and developing-country evidence, likely relevant for Tunisian cereals and dairy, points to limited storage and cold-chain infrastructure, poor transport conditions and inadequate packaging as important drivers of upstream losses (Nicastro & Carillo 2021). Climatic stress, pests and diseases, lack of technical knowledge or training, and weak coordination and information sharing between farmers, processors and markets further contribute to mismatches in supply, demand and timing, thereby increasing FLW (Delgado et al. 2020; Anand & Barua 2022).

- **Downstream: processing, food Service, retail and households**

At the downstream end, a Tunisian university canteen study identifies several post-consumption waste drivers, including poor sensory quality and presentation of meals, in part due to low-cost subsidized ingredients, old trays and unappealing displays (Ismail et al. 2022). Inadequate menu

planning and demand forecasting, with portions not adjusted to daily fluctuations in student numbers, lead to substantial quantities of non-served food. Weak operational procedures and logistics such as lack of monitoring, and absence of recycling or recovery systems, further exacerbate waste (Ismail et al. 2022). Customer behaviour also plays a major role, with students frequently taking more food than they consume and generating particularly high bread waste, as reflected in a bread waste/consumption index of 46 percent (Ismail et al. 2022). More broadly, reviews from the Arab region underline the influence of consumer norms, food subsidies and generally low food prices as cultural–economic drivers that reinforce both household and catering waste patterns (Abiad & Meho 2018).

3.2. Water Productivity in Agriculture

Water productivity (WP) is the ratio of crop output to water consumed or applied; in the agricultural literature it is reported as physical productivity (yield per water) and translated into economic productivity (value per water) to reflect farmer and policy objectives. Several recent studies operationalize WP as crop yield divided by actual evapotranspiration (ET) or by irrigation water applied, and explicitly contrast physical versus economic definitions (Zhang et al. 2021; Solgi et al. 2022; Almalki et al. 2023).

Improving WP is a priority for agriculture in arid and semi-arid regions, where water supplies are limited, groundwater is often heavily exploited, and irrigation is the main driver of crop production; in such contexts, research emphasizes the need to “produce more crop per drop” to preserve non-renewable groundwater and manage the water–energy–food nexus (Solgi et al. 2022). Irrigation in these systems typically relies on groundwater pumping, creating strong pressure to raise WP in order to slow aquifer depletion, reduce pumping energy requirements and limit related emissions (Solgi et al. 2022). From a food-security perspective, higher WP allows farmers to sustain yields with less water, and crop-modelling work shows that appropriately designed deficit-irrigation strategies can increase WP while keeping yield losses within acceptable bounds, depending on climate conditions and the timing of stress (Perelli et al. 2024). Economically, improvements in irrigation water productivity or economic WP can enhance farm profitability per unit of water and reduce effective water costs; empirical studies demonstrate that combining water-saving irrigation technologies with decision support and information tools raises economic returns while lowering water use (Zhang et al. 2021; Banerji et al. 2025). Environmentally, higher WP translates into lower withdrawals, reduced energy consumption for pumping, and diminished pressure on surrounding ecosystems when it is coupled with more efficient delivery systems, smarter scheduling and optimized fertilizer use (Abdelrhman et al. 2025; Almalki et al. 2023; Solgi et al. 2022). Finally, WP is increasingly employed as a performance indicator linked to the Sustainable Development Goals, used to benchmark regional water-use performance, to map and compare crop water productivity with remote sensing, and to prioritise on-farm improvements at the water–food–energy nexus (Ghorbanpour et al. 2022; Perelli et al. 2024).

3.2.1. Measurement Methods and Recent Advances

Water productivity in irrigated agricultural systems can be quantified through multiple metrics, including Water Use Efficiency (WUE), Crop Water Productivity (CWP), Irrigation Water Productivity (IWP), and Nutritional Water Productivity (NWP), each offering distinct perspectives on water utilization in agriculture (FAO 2012; Reddy 2012; Kilemo et al. 2022).

Crop scientists express and measure WUE as the ratio of total biomass or grain yield to water supply or evapotranspiration or transpiration on a daily or seasonal basis (Sinclair et al., 1984).

CWP is usually expressed as the mass of harvested product per unit of water consumed (for example, kilograms per cubic metre) and is estimated by combining observed or modelled crop yields with actual evapotranspiration or crop water consumption (Raes et al. 2009; FAO 2012). IWP, also referred to as the productivity of applied water (PAW), instead uses the volume of irrigation water applied in the denominator, distinct from consumptive use, and is particularly useful for evaluating irrigation-system performance and conveyance losses along canals and on farms (Reddy 2012; Ghorbanpour et al. 2022). NWP extends traditional water productivity by incorporating nutrient density alongside yield and evapotranspiration. The formula is typically NWP = (yield × nutrient content) / ET, where yield is in kg/ha, nutrient content is per kg of product (e.g., g protein/kg), and ET is in m^3/ha, yielding units like g protein/m^3 (Chibarabada et al. 2017).

In addition to physical assessments of water productivity there is an economic evaluation through metrics like economic water productivity (EWP). EWP goes one step further by expressing the economic return per unit of water (for example, monetary units per cubic metre), integrating prices, costs and yields to inform farm-level and policy trade-offs between profitability and water savings (Almalki et al. 2023; Ozcelik 2024).

Conceptually, modern water-productivity metrics build on crop–water production functions (relating yield to water consumed), process-based crop growth models such as the AquaCrop family, and water-balance accounting frameworks; these tools are widely used to estimate irrigation requirements, simulate yield responses to deficit irrigation, and assess water-productivity trade-offs under different management scenarios (Raes et al. 2009; Solgi et al. 2022; Perelli et al. 2024). In practice, physical WP indicators report biophysical output per unit of water, whereas economic WP converts those outputs into monetary terms to capture value and cost implications; both perspectives are complementary and necessary for water-management and agricultural policy decisions (Ozcelik, 2024).

The methodological approaches include single-factor productivity measures, total factor productivity indices, frontier models, and deductive models (Scheierling et al. 2014). However, current research reveals significant methodological limitations: most studies either focus on field-level aspects with a single input or apply multi-factor approaches without addressing basin-level complexities (Scheierling et al. 2016). Drastig et al. (2023) found substantial variation in existing studies, suggesting a need for standardized metrics and a multidisciplinary research approach to develop more comprehensive water productivity assessment frameworks.

3.2.2. Factors Influencing Water Productivity in Agriculture

Water productivity depends on irrigation systems, genetics, on-farm management, climate, technology, and policy; targeted interventions (micro-irrigation, deficit irrigation, mulching, precision tools) commonly raise more or less the WP depending on context.

Irrigation systems: irrigation method strongly alters how much water reaches roots, evaporates, or percolates, so system choice often yields the largest immediate WP differences; research compares micro-irrigation, sprinkler, furrow and sensor-enabled systems across yields, evapotranspiration and irrigation water productivity. Drip systems often give the largest yield and WP gains in experiments because it delivers water directly near roots, reduces soil evaporation and deep percolation (Kumar et al. 2023). In arid-zone experiments, sensor-based and subsurface drip systems have been reported to increase irrigation water productivity by up to 29% and crop yields by more than 25% compared with furrow irrigation, illustrating their potential to enhance both productivity and water-use efficiency (Oiganji et al. 2025). However, modelling studies show

important trade-offs: while drip and subsurface drip irrigation improve irrigation efficiency and water-use efficiency, they can, in some cases, raise the blue water footprint, and higher irrigation intensity can further improve WUE at the cost of increased blue water use (Zhuo & Hoekstra 2017). This implies that gains in one water-productivity indicator do not automatically translate into reductions in others, such as the blue water footprint, so performance must always be evaluated against the specific target metric chosen for management or policy purposes (Zhuo et Hoekstra 2017; Banerji et al. 2025).

Crop genetics and varieties: genetics shape intrinsic crop water use and the potential for WP gains. Crop genetics influence WP via root architecture, transpiration efficiency, phenology (growth duration), and stomatal behaviour; molecular and physiological approaches can link carbon gain to water loss and guide breeding for higher WP (Alharbi et al. 2024).

Agronomic practices: such as optimizing planting density and timing aligns peak water demand with water availability; seed priming and row orientation also affect and WP (Roth et al. 2013). Organic mulching improved WUE by about 4% and synthetic mulching by about 10%, while reducing blue water footprint by 8% and 17% respectively in model experiments on winter wheat (Morison et al. 2008). Conservation agriculture (reduced disturbance, residue cover) and practices that raise soil organic carbon increase soil moisture retention and can improve WP in multiple reviews (Roth et al. 2013; Roy et al. 2023). Management bundles (mulch + optimized fertilization + precision irrigation) are repeatedly reported to deliver compound WP gains; the absolute magnitude depends strongly on baseline practices, soil and climate.

Climate and environmental drivers: such as temperature, rainfall patterns, humidity and climate variability determine crop water demand and available supply and therefore modulate achievable WP; climate change alters both demand (evapotranspiration) and supply (rainfall timing and reliability).

Technology innovations: such as Precision sensors, automation, remote sensing, increase the practical uptake and effectiveness of WP interventions. Technologies include Sensor-based smart irrigation, automation of micro-irrigation (drip, subsurface drip), remote sensing and decision-support tools are repeatedly identified as means to supply precise water, reduce application volume, and optimize timing (Zhuo & Hoekstra 2017; Niu et al. 2025). Sensor-based systems produced up to 29% higher irrigation water productivity and >25% higher yields versus furrow in one field trial (Oiganji et al. 2025).

Policy influence: High initial capital costs, missing technical skills, and limited demonstration projects constrain adoption; field trials explicitly call for policy support, farmer training and local demonstrations to scale sensor and subsurface systems (Oiganji et al. 2025). Reviews emphasize that economic capacity and institutional support determine which WP options are feasible for farmers (Molden et al. 2010; Banerji et al. 2025).

3.2.3. Water Productivity in Tunisian Agriculture

Durum wheat has been the primary agricultural crop for water productivity research in Tunisia between 2010 and 2025, with extensive studies examining irrigation efficiency and water use optimization. Multiple research efforts have systematically investigated durum wheat water productivity. Bhouri-Khila et al. (2021) used long-term crop modeling to analyze water use efficiency, while Chemak et al. (2018) found potential for a 28% production increase through improved technological processes. Frija et al. (2014) revealed that 31.7% of farmers applied water

volumes above economically optimal levels. Secondary research focus included fruit trees mainly olives and date palms (Ghrab et al. 2017; Dhaouadi et al. 2022). These studies examine water productivity under different irrigation strategies. Chouchane et al. (2015) indicate a comprehensive approach to understanding agricultural water management in Tunisia's water-scarce environment introducing the water footprint (WF) concept in the Tunisian context.

Water productivity in Tunisia shows significant variability across crop types, with substantial improvements possible through innovative agricultural practices and irrigation technologies. For cereals, water productivity ranged from 0.12 to 2.40 kg/m³, with cereal-legume mixtures improving to 9.07 kg/m³ (Mekki et al. 2024). Olive orchards demonstrated water productivity ranging from 0.29 kg/m³ in rainfed conditions to 0.77 kg/m³ in fertigated systems (Masmoudi-Charfi et al. 2022). Drip irrigation technologies significantly enhanced water productivity, reducing water consumption by 5,200 cubic meters per hectare and increasing tomato yields by 30-60% (Messaoudi et al. 2025). Regional variations were notable, with South Tunisia experiencing the lowest economic water and land productivities according to Chouchane et al. (2015).

3.3. The Water Footprint Approach

WF measures the volume of freshwater used to produce goods and services, encompassing consumption and pollution across supply chains (Hoekstra et al. 2009). It comprises three components: the green WF, representing rainwater stored in the soil and evaporated or incorporated into crops (particularly relevant for rainfed agriculture); the blue WF, indicating surface and groundwater consumed through evaporation or product incorporation; and the grey WF, estimating the volume of freshwater needed to dilute pollutants to meet water quality standards (Demir & Muratoglu 2025).

In agricultural products and value chains, the WF reveals hidden water dependencies, with agriculture accounting for 92% of the global WF, dominated by green water (74%) from crops like cereals and meat products. This metric aids value chain actors in identifying inefficiencies, such as high blue WF in irrigated crops (e.g., wheat in water-stressed regions), and supports sustainability by quantifying virtual water trade, where 19% of production WF serves exports, influencing food security and policy in importing nations (Fader et al. 2011; Demir & Muratoglu 2025).

3.3.1. Water Footprint Assessment Methods

WF assessment methods in agriculture vary by approach and data sources, focusing on green (rainwater), blue (irrigation), and grey (pollution dilution) components (Mekonnen & Hoekstra 2011; Demir & Muratoglu 2025).

Two primary approaches to WF calculation exist: the volumetric approach and the LCA-based approach (Lovarelli et al. 2016). While both aim to protect water resources, they differ methodologically (Boulay et al. 2013). The volumetric approach, employed in early WF analyses, links human activities to freshwater sources with a focus on water management (Hoekstra 2016), whereas the LCA-based approach, developed later, assesses impacts on water availability and scarcity (Zhai et al. 2021).

- **Volumetric-Based Approaches:**

These approaches calculate WF as total freshwater volume consumed per unit yield, often using crop models like CROPWAT, AquaCrop or Crop Water Use Model (CWUModel) to estimate

evapotranspiration divided by yield. Examples include grid-based dynamic water balance for green/blue/grey WF (Mekonnen & Hoekstra 2011) and hydrology models at 0.5° resolution for major crops (Fader et al. 2011).

WF calculations generally rely on three main methodologies: empirical methods, statistical methods based on regional water balance, and hydrological modelling-based methods (Luan et al. 2018). WF analysis can integrate one or more of these methods for comprehensive assessment. Empirical methods, like CROPWAT, base calculations on daily soil water balance to estimate water use. Figure 1 illustrates the core empirical method.

Most studies follow the Water Footprint Assessment Manual by Hoekstra et al. (2011), which emphasizes consumptive and pollutive WF components. statistical methods apply water balance principles, calculating evapotranspiration (ET) as the difference between inflows and outflows (Luan et al. 2018). Finally hydrological modelling methods model all hydrological cycle parameters to derive WF, enabling analysis of factors like soil types, distribution, and farm management practices.

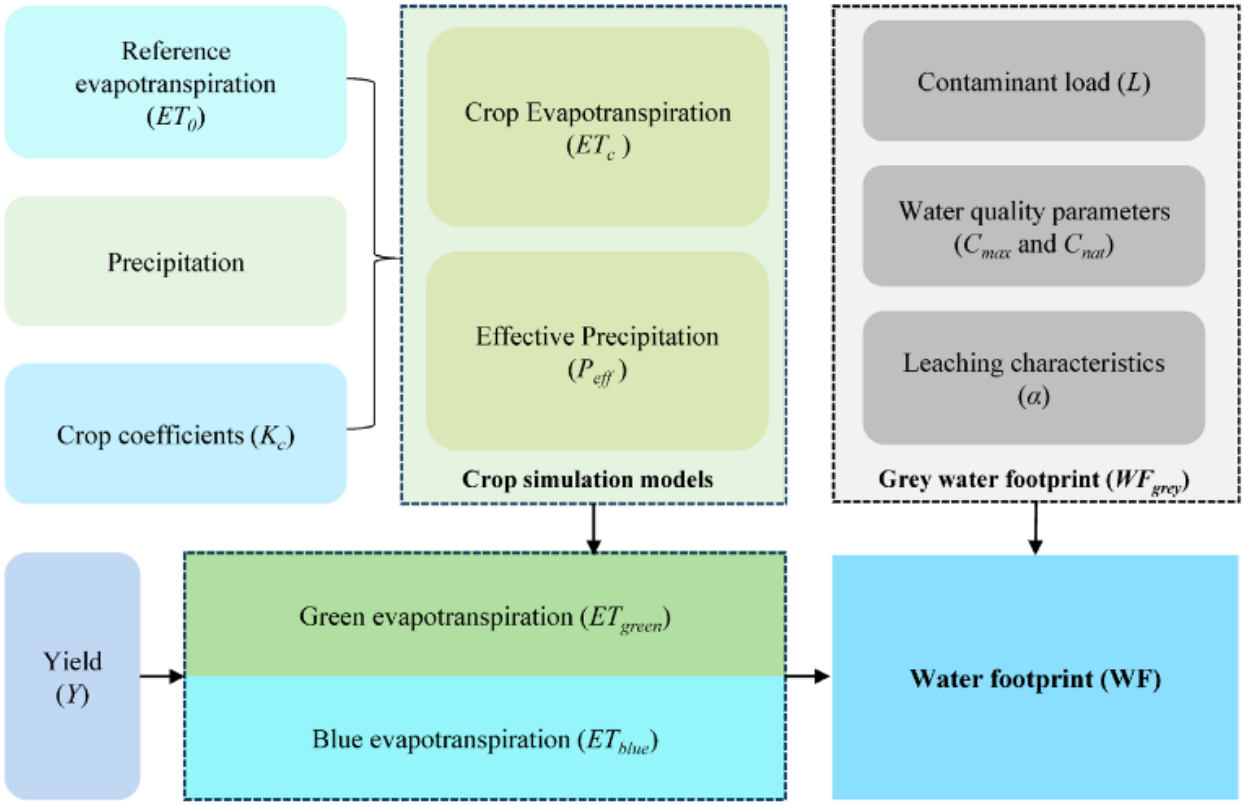

Figure 1. Typical methodology of WF calculation (Demir and Muratoglu 2025).

- **LCA-Based Approaches**

Life Cycle Assessment integrates WF into broader environmental impacts, tracking direct/indirect water use across supply chains. ISO standards structure LCA evaluation in four principal phases for WF assessment: goal and scope definition, life cycle inventory (LCI) analysis, life cycle impact assessment (LCIA), and interpretation (Klöpffer 1997) (Figure 2). The initial phase establishes the

study's objectives and delineates environmental impact boundaries. LCI compiles all relevant input and output data, while LCIA quantifies potential impacts by applying characterization factors to LCI results, such as converting emissions like CH4 and N2O to CO2 equivalents for global warming potential (Abd Rashid & Yusoff 2015). Interpretation synthesizes LCIA findings and explores mitigation strategies (Brentrup et al. 2004).

LCA scholars' critique volumetric WF for neglecting environmental and social consequences of water consumption, contrasting with the spatially uniform impacts of carbon footprints (Wichelns 2015). Though valuable for water management, it overlooks scarcity contexts. Conversely, critics note that LCA inadequately addresses equitable water allocation despite its sustainability benefits (Hoekstra 2016).

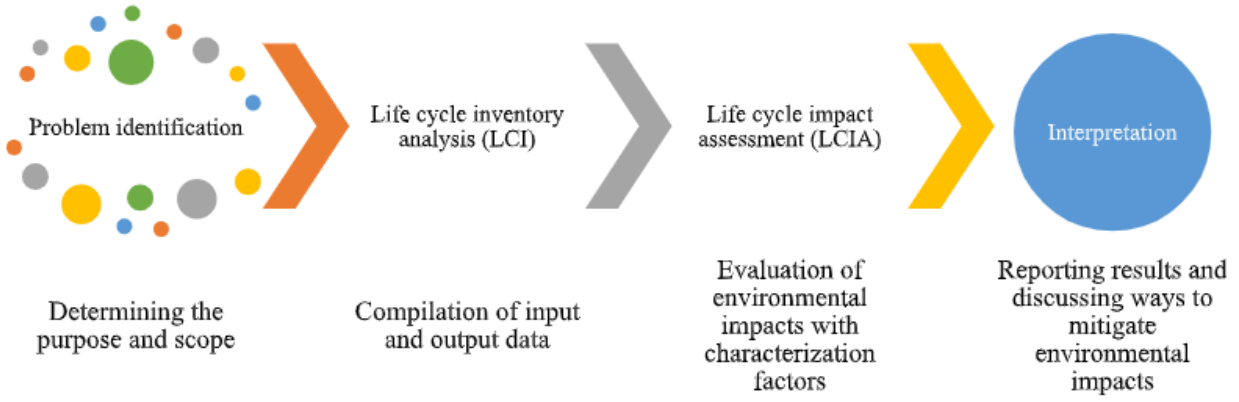

Figure 2. Stages of LCA assessment according to ISO standards (Demir and Muratoglu 2025).

3.3.2. Application in Agricultural Value Chains

Water Footprint assessment enables comprehensive evaluation of water use efficiency across the entire value chain by quantifying total freshwater consumption, including green, blue, and grey components, from production to final consumption, attributing it to specific products and processes (Zhang et al. 2013; Hoekstra 2016). In agricultural contexts, such as crop production, the WF of crop values (WFV) compares water use per unit economic value, revealing inefficiencies under complex planting structures and guiding optimized resource allocation (Hai et al. 2020). For livestock chains like dairy, full value-chain WF analysis identifies dominant indirect WF from feed crops (over 90% of total), informing strategies to enhance efficiency at each stage, from breeding to processing (Bai et al. 2018). Step-wise accumulation approaches in wheat-bread chains calculate economic water productivity by integrating physical WF with value added, pinpointing hotspots for sustainable benchmarks (Mohlotsane et al. 2018). Overall, WF assessment supports value chain optimization, scarcity analysis, and targeted interventions like improved irrigation or renewable integration, reducing WF while boosting productivity (Hoekstra 2024).

WF assessment holds specific relevance for water-stressed Tunisia, where agriculture consumes 80% of blue water reserves and groundwater overexploitation threatens production (Chouchane et al. 2015; Souissi et al. 2019; Dellaly et al. 2024). It quantifies green, blue, and grey water use at national, regional, or value chain scales, revealing that blue WF of crops represents 31% of renewable blue resources, particularly critical in southern regions (Chouchane et al. 2015; Mekki & Zitouna-Chebbi 2021). Data availability relies on national household surveys, farmer surveys, Water Footprint Network databases, and Landsat satellite imagery, but faces limitations in

differentiated crop prices between rainfed and irrigated systems, fertilizer application rates for grey WF calculation, and recent regional statistics (Chouchane et al. 2018; Ibidhi et al. 2019; Souissi et al. 2022). Methodological challenges encompass unreliable primary data, uniform price assumptions across regions, and complexities in large-scale hydrological balances, which remote sensing via NDVI and AquaCrop models partially address (Chouchane et al. 2015; Dellaly et al. 2024).

WF analysis pinpoints high water consumption stages in Tunisian value chains by quantifying green, blue, and grey components across production processes, identifying crop production as the dominant contributor at 87% of the national WF, with olives, wheat, and barley exhibiting low economic water productivity compared to tomatoes and potatoes (Chouchane et al. 2015). In the olive oil value chain, agriculture and processing phases emerge as primary water users, where irrigated systems and continuous-two-phase processing show superior efficiency over rainfed or traditional methods, targeting these for optimization (Elfkih et al. 2023). As mentioned before, dairy chains reveal feed production accounting for 87% of milk WF, driven by over-irrigation of crops (Ibidhi & Salem 2020), while field-level surveys confirm under- and over-irrigation as key waste sources, equating to 470 million Tunisian Dinars in annual economic losses (Chebil et al. 2019).

For water waste and pollution, WF highlights irregular irrigation timing, traditional tools, and groundwater overuse, representing 62% of renewable resources, as critical inefficiencies, alongside grey WF from untracked fertilizers (Chouchane et al. 2015; Souissi et al. 2019). Linking to FLW, household consumption WF analysis identifies dietary waste as a high-WF driver (Souissi et al. 2022). Interventions target feed substitution via virtual water trade, precise irrigation scheduling, low-WF forages, and supply chain coordination, enhancing water productivity (WP) by up to 16% in dairy and reducing FLW-embedded water in wheat-like chains (Ibidhi & Salem 2020). Policy implications recommend structural cropping adjustments, improved irrigation efficiency, virtual water trade strategies such as exporting low-WF olives while importing water-intensive wheat, consumer sensitization campaigns, and targeted subsidies to reduce WF and enhance food security (Chebil et al. 2019; Souissi et al. 2019)

4. Interconnections between Value Chains, Water Productivity, and Food Loss and Waste

The reviewed literature identifies several mechanisms linking value chain performance, water productivity, and food loss and waste generation. The interconnections between agricultural value chains, WP, and FLW in Tunisia are structural and interdependent. Water productivity is not merely a physical measurement but includes an economic dimension where irrigation efficiency directly impacts the profitability and sustainability of strategic sectors such as olive oil, dates, and cereals. However, a sustainability paradox exists: private irrigation systems can be more profitable for individual farmers while wasting more resources than public systems, which undermines national-level resource efficiency (Chebil et al. 2019).

Food loss and waste are often the result of systemic inefficiencies throughout the entire chain. Beyond physical post-harvest losses, these inefficiencies include misalignments between production and market requirements. For instance, in the goat farming sector, 92% of butchers prefer fattened animals, yet only 16% of farmers engage in fattening practices, leading to a significant loss of economic value (Day et al. 2025). Furthermore, climatic pressures such as

drought act as exogenous shocks that reduce yields, which subsequently decreases the demand for harvest labour and weakens export capabilities (Verner et al. 2018).

The choice of processing technologies serves as a major lever for simultaneously improving product quality and water management. In the olive oil sector, adopting two-phase extraction systems significantly reduces waste water production compared to traditional or three-phase systems (Elfkih et al. 2023). Ultimately, strengthened coordination among various actors, from farm operators to agro-processors, is required to create positive feedback loops where water savings support the overall productivity and resilience of the value chain.

To better understand these links, one can compare the agricultural value chain to a complex irrigation system: if a canal (production) leaks or a valve (processing) is poorly adjusted, not only is the water (the resource) wasted, but the final harvest (economic value) decreases, making the entire system more vulnerable to periods of drought.

4.1. Knowledge Gaps and Future Directions

Inconsistent FLW assessment in Tunisian agriculture: Food loss and waste (FLW) receive inconsistent attention in Tunisian agricultural literature, often as secondary concerns rather than primary research foci. Studies must advance beyond post-harvest metrics to encompass production-market misalignments, climate-induced yield losses, and system inefficiencies across the entire value chain (Day et al. 2025).

Limited crop-specific, regional, and scale-specific WP data: While strategic crops like olives and cereals are well-studied, emerging sectors such as goat farming lack water productivity (WP) analysis. Geographic stratification by bioclimatic zone (arid, semi-arid) and region (north, centre, south) remains essential, as national aggregation obscures heterogeneity in water scarcity impacts; WP indicators should integrate physical metrics with economic metrics.

Incomplete WF integration for key products: Despite virtual water's recognition as a unifying policy framework linking production systems to water use choices, comprehensive WF assessments are not fully integrated into mapping Tunisia's principal agricultural products.

Missing integrated value chain frameworks: No studies simultaneously analyse value chains, WP, and FLW within unified multi-scale frameworks (farm, regional, national). Food loss quantification and water productivity metrics remain disconnected, obscuring cascade effects from production losses to downstream water waste.

4.2. Policy Implications

These recommendations emphasize institutional coordination, technology adoption, and strategic planning to enhance sustainability amid water scarcity.

- **Institutional Coordination Mechanisms**

Establishing platforms linking irrigated schemes, farms, and agro-processors fosters collaboration across value chains like olive oil, cereals, and dairy. This addresses coordination failures identified in multi-stakeholder analyses. Such mechanisms enable shared information on market demands, reducing FLW from production-market misalignments.

- **Technology Adoption and Farmer Support**

Promoting water-efficient technologies cuts wastewater while improving product quality and economic returns. Pairing these with irrigation upgrades (e.g., drip systems) and price supports for producers in olives, dates, and cereals boosts agricultural value added, countering the paradox where private systems profit farmers but waste national resources. Farmer training and subsidies overcome adoption barriers like high costs and skills gaps.

- **Water Footprint Integration in Planning**

Incorporate WF and virtual water accounting into national strategies to align crop production with water availability, favouring low-WF exports like olive-oil over water-intensive wheat imports. This supports intersectoral collaboration for drought management and agroforestry, building on existing policies like the National Water Saving Program. Consumer campaigns and targeted subsidies further reduce household WF from dietary waste, enhancing food security.

5. Conclusion

This scoping study examined the interconnections between strategic agricultural value chains, food loss and waste, water productivity, and water footprint assessment in water-stressed Tunisia. Through a structured review of academic and grey literature, the analysis addressed four objectives: evaluating assessment methodologies, mapping value chain interactions, assessing water footprint applicability, and identifying research and policy priorities. The study focused on priority sectors including olives, dates, cereals and dairy.

The findings demonstrate profound systemic linkages. Crop production accounts for 87% of Tunisia's national water footprint, with blue water consumption exceeding 31% of renewable resources. Private irrigation systems, while profitable for individual farmers, create a sustainability paradox by wasting national resources. Food loss and waste extend beyond post-harvest stages to include production-market mismatches and climate-induced yield reductions, embedding substantial volumes of wasted water. Water footprint analysis precisely identifies intervention hotspots: feed production dominates livestock chains (87-90% of total footprint), two-phase olive oil extraction outperforms traditional methods, and irregular irrigation practices drive field-level waste.

Critical knowledge gaps persist, including limited regional water productivity data, disconnected food loss and water productivity frameworks, and insufficient socio-economic analysis of farmer incentives. Policy recommendations emphasize multi-scale solutions: establishing coordination platforms between farms and processors, implementing scarcity-based water pricing, promoting water-efficient processing technologies, leveraging virtual water trade, and launching consumer awareness campaigns. These interventions could achieve up to 16% water productivity gains while reducing food loss.

By integrating water footprint, water productivity, and food loss frameworks with bioclimatic stratification, Tunisia can transform water scarcity into sustainable agricultural value creation, aligning production with national water and food security, and climate resilience objectives.

Acknowledgment

This report is produced in the frame of the project “Supporting the implementation of the Regional Water Scarcity Initiative (WSI) in the Near East and North Africa (NENA) Region” under a grant agreement (#200436) with the International Center for Agricultural Research in the Dry Areas (ICARDA - https://www.icarda.og/)”. Its contents are the sole responsibility of ICARDA and do not necessarily reflect the views of FAO, SIDA, CGIAR or INRAT.

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