Water Footprint Analysis

for Selected Agriculture Products in Egypt

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EXECUTIVE SUMMARY

BACKGROUND Egypt and the Netherlands maintain a close and long-standing trade relationship over various agriculture products. The Egyptian horticultural sector in particular plays a significant economic role in the country through its export of fruits and vegetables. However, the country is also facing various water-related challenges, including that of large water footprints associated with the production of crops in a context of limited available water resources and climate change.

PURPOSE The two-fold objective that guides this study is to understand the water footprint of various crops that Egypt exports to the Netherlands and identify opportunities to support Egyptian farmers in reducing water footprints of these crops. The selected crops are potato, onion, tomato, leaf lettuce, and strawberry.

METHOD The objective was reached through five steps. First, water footprints of the selected crops were collected from existing scientific databases. Second, found water footprints were compared to those of countries with comparable climatological conditions, namely Jordan, Morocco, and Spain, as well as those in the Netherlands. Third, recommendations were drafted for water footprint reduction measures relevant in the Egyptian context. Fourth, interviews were carried out with relevant stakeholders, both to verify results of the above steps and to explore business opportunities between Egypt and the Netherlands. Lastly, recommendations for Dutch businesses seeking to leverage Dutch expertise in smart water usage practices for Egyptian farmers were distilled based on all preceding steps.

WATER FOOTPRINT ANALYSIS This study reveals a large spread in the estimates of unit water footprints across the databases, which is likely explained by differences in field management practices and agro-climatic growing conditions across production locations within Egypt; the growing season considered (winter/summer); and the sources of input data used in the underlying simulations. Green water plays a marginal role, meaning Egyptian agricultural production is practically fully supported by blue water resources (surface and groundwater).

Average unit water footprints across crops are quite comparable, with strawberry as the most and tomato the least water intensive crop at 237 m^3/t and 145 m^3/t on average, respectively. In terms of economic water productivity, however, lettuce and strawberry generate much more economic value per drop of water than do potato, onion and tomato. Except for leaf lettuce, the selected crops have become more water-use efficient over the 1990-2019 period. However, unit water footprints are still relatively large compared to countries with similar agro-climatic conditions.

REDUCTION MEASURES Various water footprint reduction measures have been identified, including the use of improved or localized irrigation systems, improved irrigation strategies, soil covers and mulching, better fertilization management, effective weed and pest control, selection of drought and/or salt tolerant or resistant crop varieties, exogenous substance application to leaves to improve drought tolerance, and reducing food losses and waste along crop value chains. The effect on water footprint reduction and yields of those measurements in the Egyptian context has been assessed based on an extensive literature review.

BUSINESS OPPORTUNITIES Various opportunities have been identified for Dutch businesses to support Egyptian farmers in adopting some of the recommendations that could help reduce the water footprint of the selected crops. Opportunities related to the production phase specifically, the whole value chain, and in facilitation and knowledge exchange can bring Dutch and Egyptian private partners together towards producing more and better food with fewer impacts on Egypt's precious water resources.

1. BACKGROUND

Egypt possesses a diverse horticultural sector that plays a significant economic role within the country. Horticulture makes a substantial contribution of 11% to the GDP, employs 20% of the labor force, and marks 13% of Egypt's total export volume. Key crops include vegetables and citrus fruits.

Egypt is also an extremely arid country, with average precipitation ranging between less than 1 mm/year in upper Egypt to 200 mm/year in Alexandria along the North coast. Total water demand amounts to 115 billion m^3/year, a multiple of the 55 billion m^3/year that flows into the country from Sudan through the country's major source of water, the Nile River. Deficits are covered by exploitation of fossil groundwater and re-use of water. The agriculture sector is responsible for approximately 80% of water consumption.

Furthermore, Egypt is impacted by climate change. While the country has implemented water recycling schemes, further climate adaptation and water-related measures are needed to increase water-use efficiency, preserve soil fertility, and reduce the excessive use of pesticides and fertilizers—all with the overarching aim to ensure long-term productivity and domestic food security.

Despite these challenges, Egypt's agriculture sector is exporting various products, also to the Netherlands. The total value of agriculture exports from Egypt to the Netherlands amounted to EUR 178 million in 2022. Agricultural trade between the two countries is historically high, mainly in vegetable seeds (import), potatoes (in- and export) and tropical fruits (export). Also in terms of knowledge exchange and capacity building, the Netherlands is one of the main partners in the areas of agriculture and water management.

PURPOSE AND SCOPE

As a long-standing partner regarding agriculture knowledge and technology, the Embassy of the Kingdom of the Netherlands in Egypt expressed the need to identify opportunities for Dutch businesses to support Egyptian farmers in reducing their water footprint, in particular for selected popular crops that are being exported to the Netherlands. The current study is intended to be a first step in that direction.

More specifically, the purpose of this water footprint analysis is to support Dutch and Egyptian agriculture entrepreneurs to increase their environmental sustainability and climate resiliency by reducing the water footprint of selected agricultural products. Furthermore, it will help the Embassy of the Kingdom of the Netherlands in Egypt in substantiating their decision of narrowing down their focus for their so-called combi-track and further develop concrete activities under it.

The emphasis of this water footprint analysis will be on selected crops produced in the Nile Delta region of Egypt. The blue and green water footprint of the selected crops will be considered, while the grey component is out of scope (see Box 1 for terminology).

BOX 1 WATER FOOTPRINT DEFINITIONS

This study uses definitions and terminology as described in the Water Footprint Assessment Manual (Hoekstra et al., 2011). A water footprint is a comprehensive and multidimensional indicator of freshwater appropriation that goes beyond traditional and more restricted measures such as water abstracted or withdrawn (Exhibit 1).

The water footprint of a *product*, such as the selected crops that are the subject of this study, is defined as the volume of freshwater consumed to produce the product. Volumes consumed are measured over the full supply chain of the product. A water footprint thus considers not only *direct* water use but also *indirect* water use. 'Consumption' means the loss of water from the given water body in a catchment area, which occurs when water evaporates, returns to another catchment area or the sea, or is incorporated into the product. Consumed water cannot be used for other purposes in that same place and at that same time. In other words, there is an opportunity cost to its use.

A water footprint further shows water consumption volumes by *source,* using three color components. The *blue* water footprint refers to consumption of blue water resources, which include surface water and groundwater. Irrigation water, for example, is blue water. The blue component is the most important one in the Egyptian agricultural context.

The *green* water footprint refers to consumption of green water resources, which is rainwater insofar as it does not become run-off. Since rainfall is limited in Egypt, the green component plays an almost negligible role in Egyptian agriculture.

The *grey* water footprint refers to pollution and is defined as the volume of freshwater that is required to assimilate the load of pollutants given natural background concentrations and existing ambient water quality standards. Even though it can be substantial in the Egyptian context, the grey component is excluded from this study.

All components of a total water footprint are specified geographically and temporally.

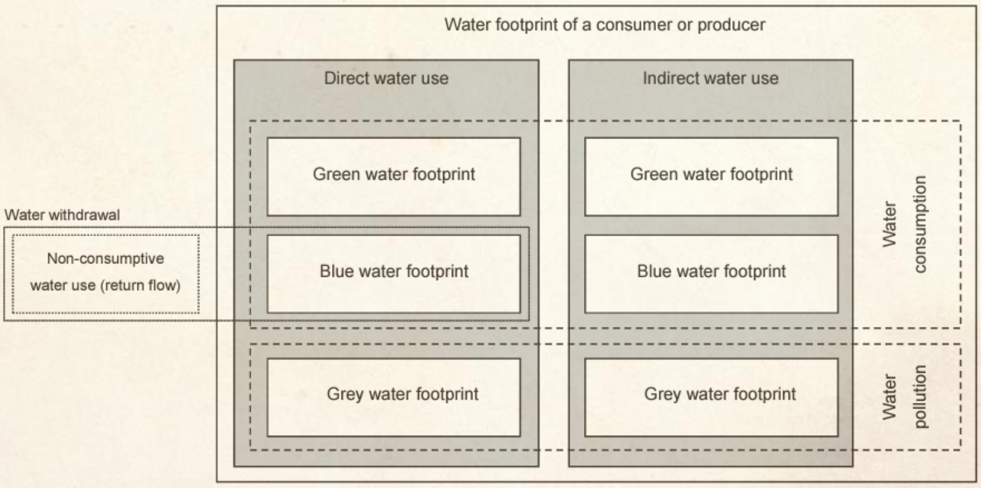


Exhibit 1: Schematic representation of the components of a water footprint. Credit: Hoekstra et al. (2011). Copyright: Water Footprint Network.

2. METHODOLOGY

The two-fold objective that guides this study is to understand the water footprint of various crops that Egypt exports to the Netherlands and identify opportunities to support Egyptian farmers in reducing water footprints of these crops.

The selected crops selected are:

- Potato (industrial for production of crisps and fries);
- Onion;
- Tomato (both protected and open field);
- Leaf lettuce;
- Strawberry.

To reach the objective, the following approach was taken. First, existing scientific databases were probed to collect data on water footprints associated with production, storage, and transportation of the indicator crops. Only databases that included at least multiple crops were considered for this step. Resulting unit water footprints were also expressed in Economic Water Productivity using export market prices.

Second, a comparative analysis was carried out between water footprints in Egypt and in countries with similar climatological conditions, namely Jordan, Morocco, and Spain, as well as in the Netherlands. To ensure consistency in the methodology underlying these national water footprints, two global databases were used that each include water footprint accounts for all five countries.

Third, recommendations were drafted for water footprint reduction measures relevant in the Egyptian context, including their advantages, disadvantages, and water saving potential. In addition to the databases found in step one, in this step crop-specific publications and databases were considered too.

Fourth, interviews were carried out with relevant stakeholders (see Table 1), both to verify results of the above steps and to explore business opportunities between Egypt and the Netherlands.

Lastly, recommendations for Dutch businesses seeking to leverage Dutch expertise in smart water usage practices for Egyptian farmers were distilled based on all preceding steps.

Table 1. Overview of stakeholders in Egypt and the Netherlands that were contacted to verify the results of the water footprint analysis and to explore business opportunities. Interviews took place over the period January-March 2024.

Name	Organization	Role	Means of contact
Piet Bosma	HZPC	Export manager	Video call on 21/2/24
Mohamed Nabil	HZPC	Senior product development manager	Video call on 21/2/24
Salah Ali	Delphy	Manager Team Egypt	Video call on 27/2/24
Dr. Amr Sabahy	Sekem	General manager	Video call on 21/2/24
Prof. dr. El-Marsafawy	Soils, Water & Environment Research Institute, Agricultural Research Centre	Chief researcher (professor)	Email exchanges

3. WATER FOOTPRINT ANALYSIS

UNIT WATER FOOTPRINTS

A literature review was carried out to collate existing scientific databases that contained estimates of water footprints of multiple of the selected crops. An overview of the databases used in this analysis and the sources behind the acronyms used throughout the text is given in Table 2. Note that all databases rely on modelling techniques to obtain water footprint statistics. Moreover, most databases cover the production phase only, i.e., the process of growing the crop in the field over the course of a growing season. They remain agnostic about the specific growing conditions they assume. Tomatoes, for example, can be cultivated in open fields or in greenhouses, yet it remains unspecified what conditions apply. However, from the modelling techniques employed, it can be inferred that open field conditions are most likely simulated. Lastly, some databases report water-related metrics such as water productivity or water use efficiency, from which a water footprint can be deduced or calculated. In such cases these metrics were converted into the desired water footprint variable.

Table 2: Overview of databases with water footprint statistics used in this study.

Acronym	Source	Time period	Spatial focus	Method used	Components included	Remarks
EM21	El-Marsafawy and Mohamed (2021)	2017/2018 winter and 2018 summer season	Delta (old and new lands) and Newlands outside the Nile valley	Modelling (CROPWAT8.0 with national statistics)	Green and blue	Average of Delta is taken for this study
Mohy23	Mohy et al. (2023)	Average over 2001-2007, 2007-2014 and 2014-2021 period.	Kafr El-Shaykh, Al-Daqhliya, Al-Nubariya, Al-Gharbiya, and Al-Beheira governorates	Modelling (CROPWAT8.0 with national statistics)	Blue only	Average for 2014-2021 period is taken for this study
Osama17	Osama et al. (2017)	Each year in 2008-2012 period, winter, Nili and summer seasons	Old lands in Lower, Middle and Upper Egypt	Modelling (linear optimization model of total water available for irrigation at the field)	Blue only	Average over 2008-2012 period is taken for this study
Abdel22	Abdelkader et al. (2022)	2020/2021	Sohag Governorate	Modelling (CROPWAT 8.0 with national statistics and farmer surveys)	Blue only	
AS22	Alobid and Szűcs (2022)	Average over 2000-2018 period	Egypt (not further specified)	Modelling (CROPWAT with national statistics)	Blue only	
MH10	Mekonnen and Hoekstra (2010)	Average over 1996-2005 period	Gridded estimates at 5 x 5 arcminutes	Modelling (CROPWAT8.0 with national statistics from global databases)	Green and blue	Aggregate value at national level is taken for this study
Mialyk24	Mialyk et al. (2024)	Each year in 1990-2019 period	Gridded estimates at 5 x 5 arcminutes	Modelling (AquaCrop-OSPy v6.1 with national statistics from global databases)	Green and blue (irrigation and capillary rise)	Aggregate value at national level over the 2010-2019 period is taken for this study

Figure 1 shows the unit water footprints of the selected crops as obtained from existing scientific databases. The first observation is that **there is a large spread in the estimates across the databases**. On the one hand, this can be explained by **differences in field management practices and agro-climatic growing conditions across production locations** (for more detail, see the next section on Water footprint reduction measures). For example, the AS22 database consistently reports the largest unit water footprints (Alobid and Szűcs, 2022), but their **spatial scope** is quite narrowly focused on Sohag governorate (Upper Egypt) where temperatures are typically higher than in the Delta. The larger atmospheric water demand induced by these higher temperatures may explain the larger unit water footprint estimates by AS22.

Note that the difference between unit water footprints at locations explicitly within the Delta and those of unspecified locations is less pronounced, which can be explained by the fact that estimates listed as Country in Figure 1 may still include—and even be dominated by—production locations in the Delta region.

Another reason for these differences is the **season that is considered**. Those databases that differentiate between summer and winter growing seasons consistently show larger unit water footprints for summer production. This is likely explained by the larger atmospheric evapotranspiration demand in the warmer summer period.

On the other hand, the modelling techniques used by these studies are remarkably similar (i.e., mostly derived from CROPWAT-based modelling approaches). An additional explanation for these differences, therefore, can be sought in the use of **different external databases and national statistics** in the calculation of unit water footprints, particularly on **yields**. After all, unit water footprints are calculated as Crop Water Use divided by the Yield. Except for the Mialyk24 database who simulate yields themselves, all databases took yield statistics from external sources. Moreover, even the Mialyk24 database scales simulated yields to national yield statistics at national level.

Figure 1 also shows that **green water plays a marginal role** and is even excluded from most databases altogether. Egypt is largely an arid country, with rainfall below 200 mm/year in the wettest parts along the coastal strip in the Delta, declining to almost non-existent rainfall in Middle and Upper Egypt. Except for some winter season crops, most production is therefore supported by blue water resources only. These findings illustrate the large dependence of Egyptian agriculture on irrigation water to sustain production.

In terms of crop type, potato, onion and tomato have the largest number of databases covering them, while lettuce and strawberry have fewer entries. **Average unit water footprints are quite comparable across crops**, although **strawberry is the most water intensive crop** at 237 m^3/t on average and **tomato the least water intensive crop** at 145 m^3/t. Lettuce (average 177 m^3/t), potato (average 189 m^3/t) and onion (average 190 m^3/t) rank in the middle in terms of water productivity.

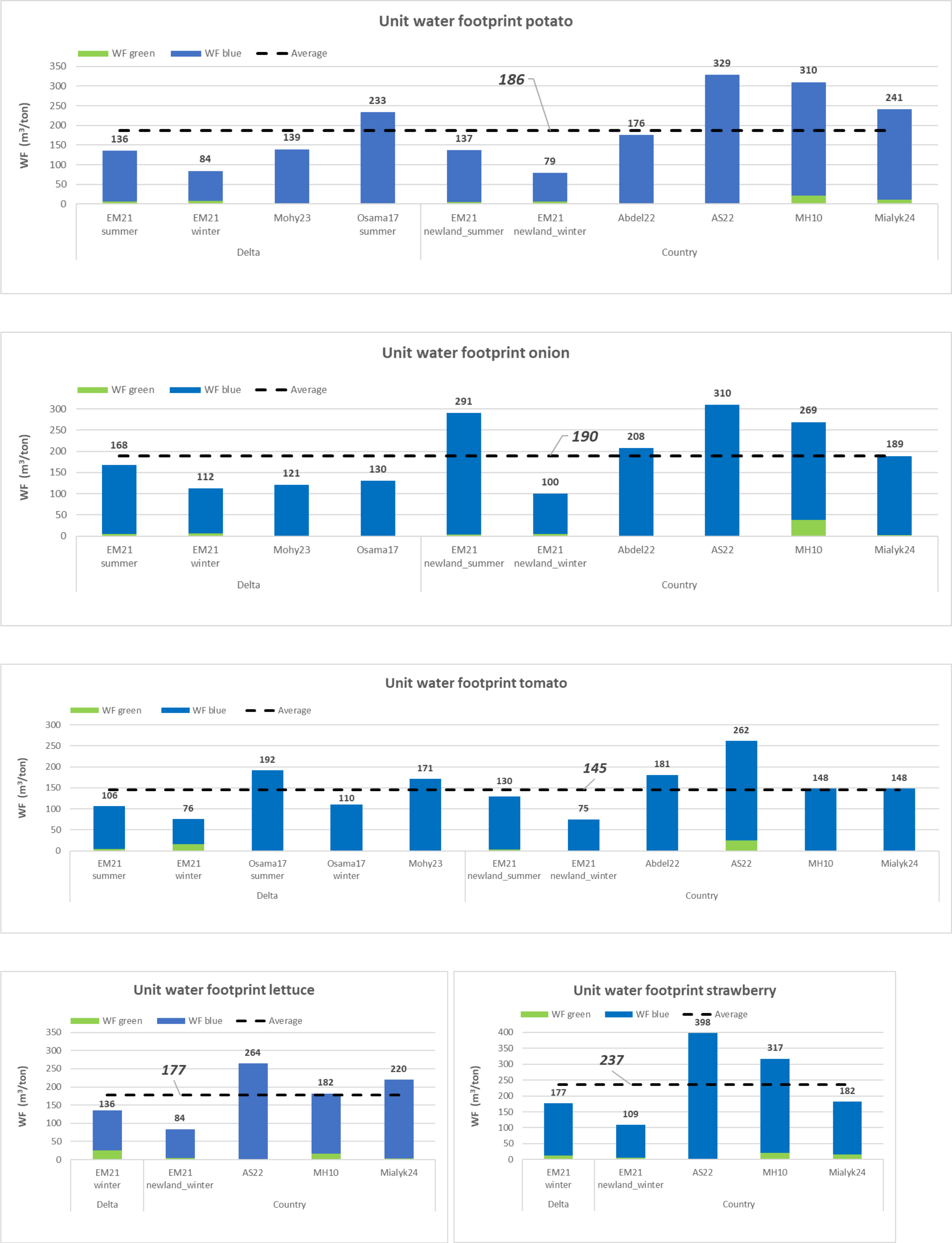


Figure 1. Unit water footprints of selected crops as obtained from existing scientific databases. The black dotted line represents the average total water footprint over all estimates. If specified, summer and winter seasons are provided separately. Estimates that do not explicitly relate to the Nile Delta are grouped under the label Country.

ECONOMIC WATER PRODUCTIVITY

The economic water productivity (EWP) is a derivative indicator of unit water footprints which relates water consumed to economic value generated. Where the water footprint indicates the drops per crop, EPW provides euros per drop. EWP is calculated by dividing the average market price for export by the unit water footprint. Market prices reflective of the 2022-2023 period were taken to calculate EWP. Since prices are volatile, a range for EWP is added.

Table 3 shows that **EWP for lettuce and strawberry is much higher than for potato, onion and tomato**, with strawberry being the most high-value crop in terms of economic value generated per drop. Moreover, prices of these high-value crops are relatively stable compared to the large volatility in prices—and thus EWP—of staple crops.

Table 3. Economic water productivity (EWP, in €/t) based on average unit water footprints and market prices for export reflective of the period 2022-2023. Brackets in the market price column indicate price volatility over the 2022-2023 period.

Crop	Average unit water footprint (m^3/t)	Market price export (€/t)	Avg EWP (€/m^3)	Min EWP (€/m^3)	Max EWP (€/m^3)
Potato	186	239 (175-310)[1]	1.28	0.94	1.67
Onion	190	212 (130-460)[2]	1.12	0.68	2.42
Tomato	145	231 (140-250)[3]	1.59	0.97	1.72
Lettuce	177	2016 (1900-2100)[4,5]	11.39	10.73	11.86
Strawberry	237	4712 (4500-4800)[6,7]	19.88	18.99	20.25

[1] https://www.statista.com/statistics/1173377/monthly-average-prices-for-potatoes-in-egypt/
[2] https://www.statista.com/statistics/1173357/monthly-average-prices-for-onion-in-egypt/
[3] https://www.statista.com/statistics/1173390/monthly-average-prices-for-tomatoes-in-egypt/
[4] https://www.tridge.com/intelligences/lettuce/EG
[5] https://www.indexbox.io/search/lettuce-and-chicory-price-egypt/
[6] https://www.tridge.com/intelligences/stawberry/EG/price
[7] https://app.indexbox.io/report/081010/818/

TEMPORAL DYNAMICS

The longest timeseries on unit water footprints for all selected crops is found in Mialyk24, who simulated unit water footprints for each year in the period 1990-2019 (Mialyk et al., 2024). An excerpt from this global database for Egypt for the selected crops is shown in Figure 2. While the database source itself does not give an explanation for these temporal dynamics, the trajectory of onions stands out in particular, as this crop seems to have become less efficient over time in terms of water use during its production. Various interviewees, however, confirmed this development, as onion production expanded into less suitable desert locations in the 1990s. After 1995, when expansion halted, a steady decrease in unit water footprints can be observed. Lettuce water footprints have remained relatively stable over the past 30 years. Tomato, potato and strawberry—and onion after 1995—have become (much) more water-use efficient, as indicated by the reduced unit water footprints over the 1990-2019 period.

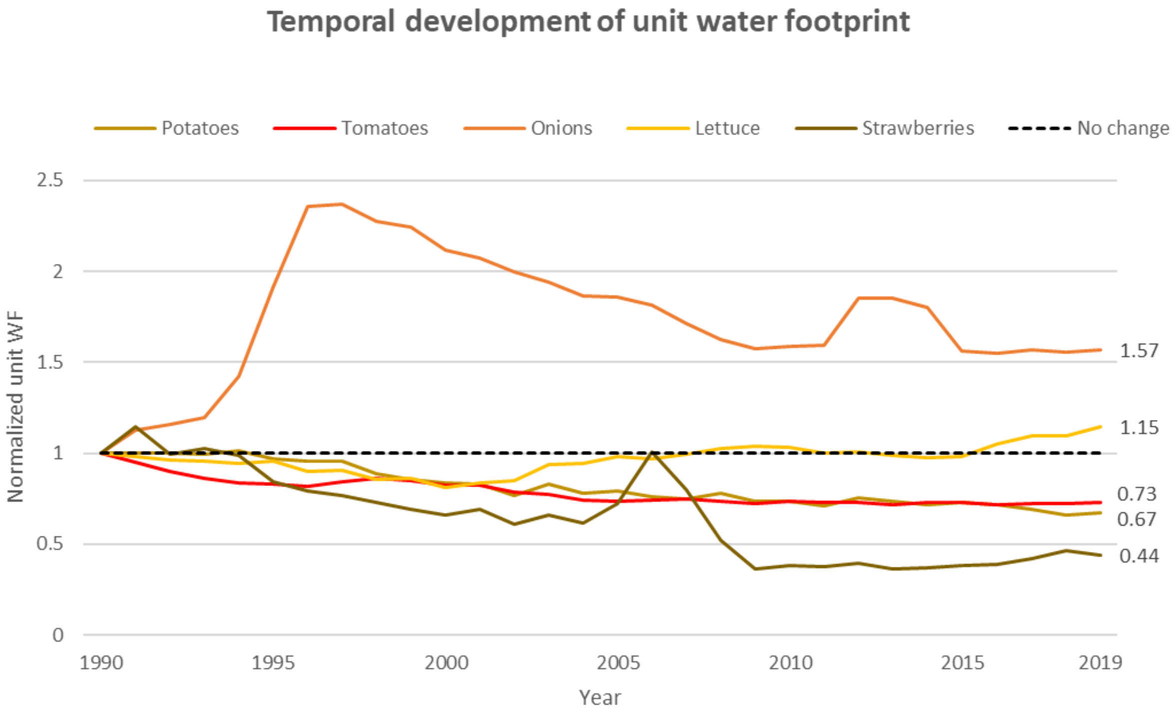


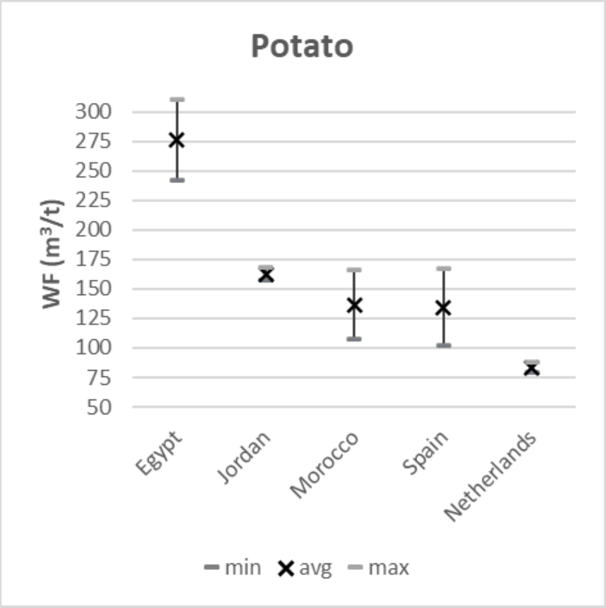
Figure 2. Temporal development of unit water footprints of selected crops in Egypt, based on Mialyk24. Unit water footprints have been normalized against reference year 1990 to ease comparison between crops. Values above 1 indicate unit water footprints (in m^3/t) are larger than in 1990 (i.e., production became less efficient in terms of water use). Values smaller than 1 indicate unit water footprints are smaller than in 1990 (i.e., production became more efficient in terms of water use). The dotted line at 1 indicates no change with respect to 1990.

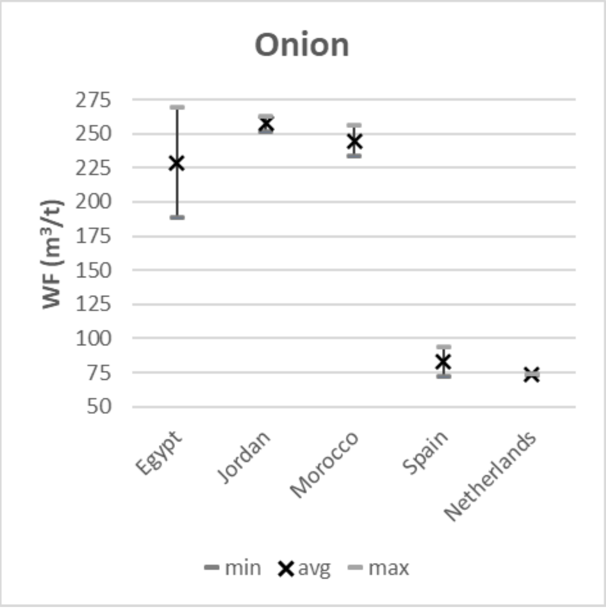
COMPARATIVE ANALYSIS

The unit water footprints for the selected crops in Egypt are compared to those in countries with similar climatological conditions, namely Jordan, Morocco, and Spain, as well as to those in the Netherlands. To ensure consistency in the methodology underlying these national water footprints, two global databases were used that each include water footprint accounts for all five countries, namely MH10 and Mialyk24. Estimates for Egypt from different databases that are included in Figure 1 are therefore excluded for this comparative analysis.

Considering all crops, Figure 3 shows that **Egypt scores in the upper echelons of unit water footprints of crops productions** as estimated by these global databases, indicating relatively low levels of water productivity. For potato and tomato, both databases report larger unit water footprints for Egypt compared to the other countries, whereas for onion, lettuce and strawberry, unit water footprints in Egypt align more closely with their climatologically similar peers (although Spain typically still boasts the smallest unit water footprints). The Netherlands show the smallest unit water footprints across all crops, indicating high levels of water productivity in the different agro-climatic conditions experienced in the Netherlands.

Note that these estimates represent national level averages that were obtained by aggregating all producers and ways of producing in a country. Specific producers in any geographical setting may therefore exhibit unit water footprints smaller than the numbers presented in Figure 3.





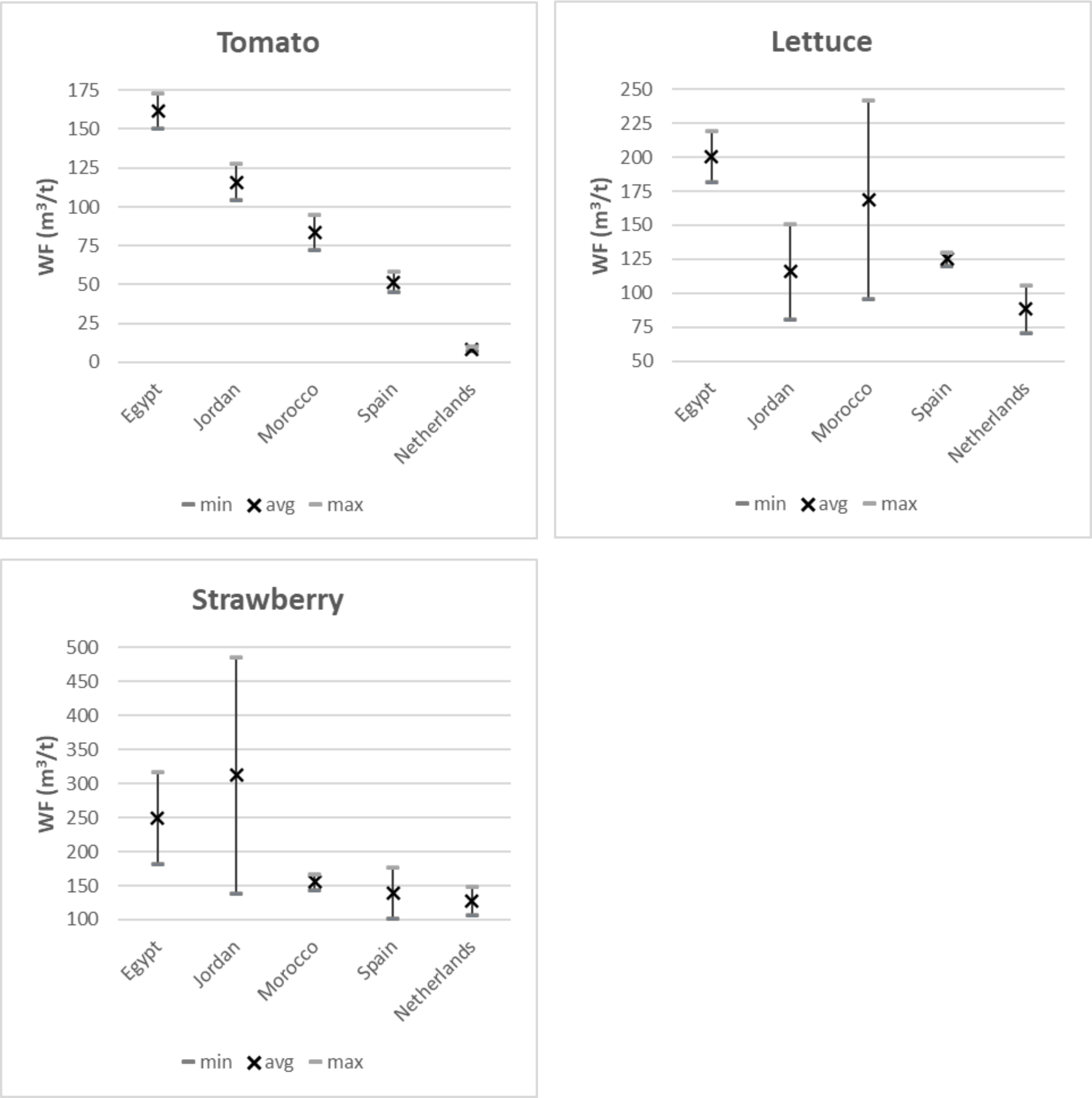


Figure 3. Comparative analysis of unit water footprints in Egypt with climatologically similar countries and the Netherlands, based on MH10 and Mialyk24 global databases.

4. GENERIC WATER FOOTPRINT REDUCTION MEASURES

A literature review was carried out on existing scientific studies to understand the potential effects of water footprint reduction measures for the five selected crops given the Egyptian agricultural context. Many measures have wider applicability than just one crop. Therefore, this chapter describes generic measures distilled from literature that have the potential to reduce water footprints across the five crops selected. The next chapter continues to describe crop-specific measures that apply more narrowly to the crop at hand.

Note that the identification of reduction measurements strongly emphasizes the production stage. This is in part because this stage is by far the most water-intensive (Hoekstra and Mekonnen, 2012), but also because there are hardly any studies focusing on water use across crop value chains.

IRRIGATION TECHNOLOGIES

Flood irrigation is the most common irrigation practice used in Egypt, especially in the Nile valley and delta region. In this traditional technique, water is applied to the entire cultivated area. Consequently, significant losses occur due to direct evaporation from standing water and bare soil, and through percolation. Improved farm water management practices can minimize such unproductive losses, for example through the use of furrows or raised-beds, where water is released into smaller channels from where it seeps vertically and horizontally to enrich the soil moisture. According to some estimations for horticultural crops in the Egyptian context, **raised beds can save 20% of the applied water under surface irrigation while increasing yields by 15%** (Ouda et al., 2020b).

The **use of modern and more efficient irrigation techniques** can significantly reduce the water required by crops for optimal growth. Often referred to as localized systems, these irrigation technologies apply water more directly to where the plant needs it, thus minimizing water loss through non-productive evaporation from the soil. Localized systems include micro-sprinklers, bubblers, surface drip, and subsurface drip systems. In such systems, water is distributed under low pressure through a piped network in a pre-determined pattern and applied through small discharges to each plant. Conveniently, these systems can double to supply fertilisers on demand (a process known as fertigation), making these nutrients more readily available to the crops. Localised irrigation systems have already proven their considerable potential to reduce unit water footprints in many regions and contexts—not only by reducing crop water use, but also by increasing yields, averaging reductions of 5% to15% in different climate conditions (Chukalla et al., 2015).

While promising, localized irrigation is not suitable for all Egyptian growing conditions. First, in applying small yet frequent discharges to the plant, many systems require an almost continuous supply of water. This is not always possible, especially in the Egyptian Delta region. Here, water from the Nile is supplied to farmers through canals with cycles of 5 to 20 days, depending on the season. Second, high levels of salinity experienced in particularly the heavy soils of the Delta region require leaching to avoid the building up of salt in the soil profile. Certain practices are recommended to reduce the risk of salinisation to an extent, such as the use of leaching factors during each irrigation event (also applied for localised irrigation), the use of certain crop rotation schemes (i.e. combinations with rice) or application of regular flooding events (i.e. during land preparation) (Mohamed, 2017). However, get rid of salts from soil in arid environment is intrinsically linked with an increase in water withdrawal.

IRRIGATION STRATEGIES

Where the irrigation technology dictates how water is applied to crops, the irrigation strategy prescribes how irrigation scheduling is managed. **The irrigation strategy selected can have a profound impact on the unit water footprint of crops**. Not all technologies are compatible with all strategies, but the following major strategies can be deployed under most localized irrigation technologies: full irrigation (i.e. the reference strategy in which the plant receives it full crop water requirement), deficit irrigation (DI), partial root-zone drying (PRD), and pulse irrigation.

Deficit irrigation

In a deficit irrigation (DI) strategy, crops are deliberately provided with less water than they require for optimal growth. DI seeks to maximize the marginal benefit of each added drop of water. In doing so, DI strategies can significantly reduce crop water use at limited cost in terms of reduced crop yield—the net effect being a smaller unit water footprint (Ouda et al., 2020a). Depending on drought tolerance of the crop at hand, applied irrigation can be reduced by 10 to even 50%. DI can be applied either at specific stages of the plant's growth cycle or during the entire planting season. When yield losses have to be balanced against water saving, the former objective is typically favoured over the latter. However, particularly in water scarce regions, water savings associated with DI strategies can make economic sense, even at a minor cost to yields. **DI strategies, if well manage, can easily reduce the unit water footprint values up to 10-30% under different irrigation technologies** (i.e. furrow, sprinkler, drip and subsurface drip irrigation)and different climate conditions (Chukalla et al., 2015).

Partial root-zone drying

Partial root-zone drying (PRD) is a specific form of a deficit irrigation strategy, where water is applied to a specific part of the root system in an alternating pattern. The technique essentially involves irrigating approximately half of the root system of a crop, while the other half is left dry. This practice trains the plant to be more efficient with the water it receives. During the early stages of water stress, a hormone (called Abscisic Acid-ABA) is synthesized in the drying roots of the crop, thus extending photosynthetic activity (Iqbal et al., 2020). Various studies on PRD and DI showed that when the same amount of water is applied, PRD resulted in higher yields, and of higher fruit quality, compared to regular DI strategies (Iqbal et al., 2020). Although not restricted to these systems, PRD is commonly used with furrow irrigation (where furrows are wetted alternatingly) or surface and subsurface drip irrigation systems.

Pulse irrigation

A well-designed irrigation schedule is essential to prevent overapplication of water while at the same time maintaining high crop yields. The number and quantity of irrigation events have a profound effect on how the water becomes available to the plant roots, but also influences the air-water interaction in the soil pores. Drip irrigation technology is typically characterised by frequent irrigation events (i.e. every 1 or 2 days) with a low rate (i.e. 1.2 to 4 litres per hour). However, in some specific cases such as heavy soils or soil-less materials, traditional scheduling can induce stress due to a lack of oxygen or water. Pulse irrigation, which is characterised by the application of short drip irrigation pulses (5 to 15 min), with a very low flow (<1 l/h) and high frequency (several times per day), can improve water availability for the roots, reducing the risk of oxygen stress and leaching (Rank and Vishnu, 2021).

Adjustments in the planting date

Related to the irrigation scheduling is the planting date and the timing of the phenological stages during the growing season, since this planting schedule influences crop evapotranspiration, and therefore unit water footprints. A well-designed planting schedule takes into account both historical records as well as weather forecasts. Relatively minor adjustments in the planting calendar of even just a few days can already expose the crop to a lower evapotranspiration demand over the crop cycle, saving water in the process (Mancosu et al., 2015).

SOIL COVERS AND MULCHING

Soil covering or mulching refers to a technique or practice where the soil surface is covered with natural and/or synthetic materials. This practice specifically targets unproductive evaporation from the bare soil close to the crop and is particularly effective in irrigated production systems. Furthermore, mulching helps suppress emergence of weeds which compete with the crop for water and nutrients, decrease soil erosion, and reduce water and fertilizer runoff from the field. Mulching can be used at different stages of the crop cycle, although it is usually most effective in the early stages when crop canopy is minimal and more bare soil is exposed. Materials suitable to use for soil cover are hay, leaves, manure, compost, vermi-compost, wood, bark, cocoa hulls, rice straw, wheat straw, peanut hulls, plastics, synthetic black polyethylene, gravel, and geo-textiles. Some organic materials can even become a source of organic matter and nutrients as they decompose over time, improving soil water related properties. Although very effective in reducing evaporation and weed suppression, synthetic covers can also be a barrier for the infiltration of rainfall. The effectiveness of mulching in reducing water consumption has been proven worldwide, with average reductions in the unit water footprint values going from 5% to 20% for organic and synthetic covers respectively (Chukalla et al., 2015).

FERTILIZATION MANAGEMENT AND SOIL AMENDMENTS

Another factor critical to achieving high yields and low unit water footprints is the availability of nutrients, particularly Nitrogen and Phosphorus. In terms of fertilization management, the type, quantity, timing, and sourcing of the fertilizer are relevant parameters that influence crop response and thus crop water footprints.

For type, the composition should be optimized for the soil at hand, based on accurate assessments of actual soil fertility and soil characteristics.

For quantity and timing, avoiding overapplication and applying nutrients at the right moment in the phenological stage are important, since excessively applied or wrongly timed nutrients may leach into groundwater or runoff into surface water, contributing to the eutrophication of freshwater bodies. An effective technique overcoming such adverse effects of fertilizer application, particularly in localized irrigation systems, is fertigation. Under fertigation, water-soluble fertilizers are injected into the irrigation system that delivers nutrients with the irrigation water directly or close to the roots at the right time during the growth cycle.

However, if fertilizer are not managed properly, undesirable effects may follow. According to Wang et al. (2023), there is a significant positive correlation between the amount of chemical fertilizer applied and the water footprint of crops, where grey water value is also considered. Despite the positive effects of fertilizers on yields, their overuse can lead to pollution. This implies their effect is more strongly felt on the grey water footprint than on the reduction of the blue and green water footprint.

For sourcing, nutrients can be sourced from mineral or organic sources. The latter are often locally available and can—depending on their nutrient content—be a source of organic matter, improve some of the water related properties of the soil, and enhance soil health through the stimulation of microbiological activity. The use of humic substances as amended for soils can also have a positive effect on unit water footprints, both through its nutrient supply and by improving water-related characteristics of the soil (Selim et al., 2009).

WEED AND PEST CONTROL

The next factor affecting unit water footprints is weed and pest management. Effective weed and pest control influence water use of crops both by reducing the competition for resources with the weeds and by supporting crop health. Weeds penalize crop yields by competing for light, nutrients, water, and space. At a global scale, the claiming of soil water by weeds is so significant that it threatens the productivity and profitability of several crops (Singh et al., 2022). Methods for weed and pest control include physical (e.g. soil covering/mulching), mechanical (e.g. manual removal, tillage, thermal or even laser weeding), cultural (e.g. crop rotation), technical (e.g. subsurface irrigation), biological (e.g. grazing or biocontrol), and chemical solutions (e.g. application of herbicides). Their relative suitability and effectiveness in reducing water footprints, however, are highly context specific. Regarding chemical control, the most common method used in agriculture, it is important to note that as with chemical fertilisation, inappropriate management of herbicides and pesticides can lead into higher water footprint values, especially when grey the water footprint is considered. The use of precision agriculture, both for the application of fertilisers and herbicides, can therefore mitigate the negative effects on the grey water footprint (Borsato et al., 2018).

DROUGHT AND SALT TOLERANT CROP VARIETIES

Drought-resistant, drought-tolerant or salt tolerant crop varieties are designed to better handle conditions of water stress comparted to conventional cultivars while maintaining yield levels. These qualities make these varieties particularly useful for application in water scarce environments and/or when deficit irrigation strategies are foreseen. During water stress periods, however, several other stresses typically occur at the same time, such as high temperatures, high solar irradiance, and nutrient toxicities or deficiencies. These interacting stresses make breeding for drought resistance properties a complex process. Although drought resistant varieties are already commercially available from seed producers for almost all the crops selected in this study, little information is publicly available on their performance related with water productivity.

INDUCING PLANT RESISTANCE BY THE USE OF EXOGENOUS SUBSTANCES AND BIO-STIMULANTS

Various studies have reported evidence that application of certain substances to the leaves of plants can also enhance crop drought resistance. Osmoprotectants, for example, support a crop's tolerance against water stress by maintaining turgidity of cells under stress while increasing the rate of photosynthesis (Hayat et al., 2012). The use of Chitosan and Glycine betaine are other examples. Chitosan is a natural biopolymer produced from the exoskeleton of aquatic crustaceans that at lower concentration can mitigate the effect of drought stress and stimulate growth (Sharif et al., 2018). Glycine is an amino acid derivative that is naturally produced in certain plant species to cope with drought stress, and promotes, among other, plant growth and water use efficiency (Ashraf and Foolad, 2007). The use of such substances is typically recommended under deficit irrigation strategies.

The application of bio-inoculants/stimulants, living organisms containing strains of specific bacteria, fungi, or algae to the soil can also enhance the fixation of nitrogen from the air or the solubilization of inorganic phosphate and micronutrients, making them readily available to plants. These agents can also provide physical barriers against pathogens, stimulate plant growth, and help decompose organic residues, improving the water related properties of the soil (Shahwar et al., 2023).

REDUCING FOOD LOSSES AND WASTE IN VALUE CHAIN

An often overlooked strategy to reduce total water consumption related to the production of agricultural products is to reduce losses and waste along the value chain. Food losses refer to discarded or wasted food at the retail or consumer level, while food loss is the food mass discarded or lost along the journey from production, post-harvest, storage, transport, and processing stages. Considering food waste alone, according to the Food Waste Index Report (UNEP., 2021) the global average food waste is estimated at 121 kg/capita/year, with 60% of the food lost at household level (74 kg/capita/year), 26% at food service (32 kg/capita/year) and 14% during retail (15 kg/capita/year). In Egypt, the estimated food waste at household level alone is estimated at 91 kg/capita/year, far above the global average. The associated water losses are estimated at 25% of the total water footprint of crop production, which comes down to 86 m^3/capita/year for North African countries (Kummu et al., 2012). Assuming 109 million inhabitants for Egypt, this means that over 9 billion m^3 is wasted annually due to food waste alone.

Studies on food losses are less prevalent, but an analysis by Siam et al. (2018) on food losses and waste up to retail of tomato in Egypt (i.e. considering all steps of the value chain, from production and harvest, to transportation, storage, exportation, and retailing) shows that losses range between 30% to 60% of the total tomato production by weight. Investing in better picking and packing methods, packaging materials, pre-cooling facilities, and transportation modes, tomato losses could be reduced by 15 to 35%. Processing tomatoes locally (i.e. sun-dried tomato or tomato paste) can also reduce losses along the tomato chain while increasing added value. Similar strategies likely apply to the other selected crops.

5. CROP-SPECIFIC WATER FOOTPRINT REDUCTION MEASURES

A literature review was carried out on existing scientific studies to understand the potential effects of water footprint reduction measures for the five selected crops given the Egyptian agricultural context. This chapter describes crop-specific measures that apply to the five selected crops. Note that most of the studies assessed are based on field experiments under specific control conditions. Caution should be taken, therefore, to project or extrapolate reported results to conventional farming settings.

POTATO

Potato is considered a drought-sensitive crop that is susceptible to yield losses in case of drought stress, mainly due to its shallow rooting system (Djaman et al., 2021). Drought susceptibility of potato depends on the variety, developmental stage, morphology of the genotype, and the duration and severity of drought stress (Nasir and Toth, 2022). Best agronomic practices that seek to reduce water use while maintaining yield levels therefore take these factors into account. According to Abdel-Hameed et al. (2022) there is a clear positive relation between reduced unit water footprints of Egyptian potatoes and their yields, meaning an increase in yield goes hand in hand with a reduction of water needed per ton of product.

In terms of irrigation technology, according to some studies implemented under Egyptian conditions, the blue water footprint of potato can be reduced to values below 90 m^3/ton when drip irrigation method is applied (Table 4), which is much lower than the average values reported in e.g. Figure 1. Other pressurised irrigation methods are also suitable for potato production, but these are not very common in the Egyptian context. The use of sprinklers, with an average irrigation efficiency of 75%, can also reduce the water footprint of potato production, particularly because it reduces the negative effects of low-oxygen stress usually associated with flood irrigation. Subsurface drip irrigation (SSDI) can effectively reduce direct evaporation of water from the soil, since water is applied directly to the root zone.

Table 4. Blue water footprints (WF_{blue}) of potato irrigated with drip technology under different soil and climate conditions.

Author	Location	Soil type	Description of irrigation system	WF_{blue} (m^3/ton)
Meligy et al. (2020)	Qalyubiah Governorate	Silt loam	2 l/hr discharge	88.5
El-Mageed et al. (2017)	Menofia Governorate	Sandy loam	4 l/h discharge	75.3
Badr et al. (2022)	West side of Nile Valley	Sandy	In-line drippers at 40 cm distance, 2.5 l/hr discharge	75.7
Eid et al. (2020)	Qalyubiah Governorate	Clay	In-line drippers at 25 cm distance	83.3

In terms of irrigation strategy, deficit irrigation has been extensively explored under Egyptian conditions, showing that unit water footprints can be reduced considerably, especially when deficit irrigation is applied during the late stages of potato production (Djaman et al., 2021). For a sandy soil experiment located in west side of Nile Valley of Egypt, Badr et al. (2012) found that the limiting irrigation water supply by 50% during the last part of the crop cycle (from middle of tuber bulking up to maturity stage) reduced the blue water footprint by 16% from 78 m^3/ton under optimal irrigation conditions to 66 m^3/ton under deficit irrigation, while barely affecting yields (43 tons/ha vs 40 ton/ha respectively). According to the authors, the timing of the DI listens very closely, however, since a reduction of irrigation during the tuber initiation stage was found to not reduce the water footprint but significantly reduced yield.

For an experiment carried out on a light clay in Qalyubiah Governorate, Eid et al. (2020) found that the blue water footprint could be reduced by 14% (from 83 m^3/ton to 71 m^3/ton) when 80% of the total water demand of the crop is applied during the whole crop cycle, while tuber yields of potatoes and suitable tuber quality were barely affected.

In a different context of Saudi Arabian potato production (similar climate conditions to Egypt both and on sandy loam soil), Mattar et al. (2021) found that a reduction in the blue water footprint of 8 to 13% is possible when deficit irrigation is applied at 70% and 50% of the total crop water demand, respectively. However, a considerable decline in yields was found, especially when a 50% DI strategy was applied. Moreover, they concluded that the yield response factor of potatoes to water shortages is a little below 1, indicating that potato can tolerate water deficit to some extent, which will allow the yield to be maintained while reducing water loss in arid environments. From an extensive literature review, Nasir and Toth (2022) conclude that there is a variable response of different potato genotypes to different degrees of drought, thus breeders should select promising genotypes to develop drought-tolerant potato cultivars.

Partial root-zone drying has been also tested under Egyptian conditions. For a two year experiment at the west side of the Nile Valley and on sandy soil, Badr et al. (2012) found that blue unit water footprints can be reduce by 20% by applying PRD. However, yields could be significantly affected with up to 10% reductions observed. The effectiveness of this technique strongly relies on soil properties, and it is most suitable for light soils (Ahmadi et al., 2010). However, Iqbal et al. (2020) conclude from their extensive literature review that there is not such clear evidence yet about the benefits of the PRD strategy in potato production, particularly since many experiments report non-trivial reductions in yield and/or tuber quality (size).

For a two year experiment with two localised irrigation systems (surface and subsurface drip irrigation) on Abo-Ghaleb Governorate on sandy soil, Eid et al. (2019) found that the use of several daily irrigation pulses (2 to 4) reduces the blue unit water footprint by 20-25% compared with only 1 application. However, when this technique is used under deficit irrigation, the salts can accumulate around the crop roots, has a negative consequences for the yields.

Selim et al. (2009) tested the effects of humic substances as soil amended during fertigation, both with SDI and SSDI at El-Nubaria Governorate. Although the authors didn't report values on water footprints in their study, it could be derived that their application of rate of 60kg/ha to 120 kg/ha of humic substances with the irrigation water had a positive impacts on yields.

They found that using the same amount of water, SSDI improve the quality of crops, as well as the concentration of nutrients in the tubers. This strategy also helped maintaining soil fertility after harvesting.

Differences in planting dates are also reported to affect potato water demand. For an experiment in Qalyubiah Governorate for two seasons of winter potato, Meligy et al. (2020) found that delaying the planting date from mid-December to end of January increased the unit water footprint. They reported values of 60 m^3/ton by sowing on the 18th December, 95 m^3/ton for 7th January and 125 m^3/ton for 27th January. This increase is mainly explained by a reduction in yield, but also by an observed increase in crop evapotranspiration due to higher temperatures over the postponed growing season.

A summary of the most effective measures in terms of unit water footprint reduction reported by the some of the cited literature is given in Table 5.

Table 5. Summary of the most effective measures to reduce unit water footprints (WF) over the control situation in potato production in the Egyptian context according to the consulted literature.

Reference	Location and soil type	Best strategy tested	Yield reduction	WF reduction
Badr et al. (2012)	West side of Nile Valley (sandy soil), using DI irrigation	DI - 50% of ET during the middle of tuber bulking up to maturity stage (100% ET during the rest of the cycle)	8%	16%
Eid et al. (2020)	Qalyubiah Governorate (clay soil), using SDI irrigation	DI – 80% of ET during the whole growing season	8%	14%
Eid et al. (2019)	Abo-Ghaleb Governorate (sandy soil), using SDI and SSDI irrigation	Several irrigation pulses (2 to 4 per day)	-	20%
Mattar et al. (2021)	Saudi Arabia (sandy loam soil), using SDI and SSDI irrigation	SDI versus SSDI DI – 70% of ET during the whole growing season	-4% (increase) 15%	4% 11%
Selim et al. (2009)	El-Nubaria Governorate (sandy soil), using SDI and SSDI irrigation	SSDI with 120 kg/ha of humic substances	-	17%
Meligy et al. (2020)	Qalyubiah Governorate (clay soil), using SDI	Early planting date (Mid-December) and DI - 80% of ET	-40% (increase)	60 to 80%

Note: SDI is surface drip irrigation; SSDI is subsurface drip irrigation; DI is deficit irrigation; PRD is partial root drying.

ONION

For various regions of Egypt, Ouda et al. (2021) estimated the blue water footprint of onion under two different irrigation systems, i.e. traditional flooding and raised beds. They estimated that blue unit water footprints were 10-20% smaller with raised beds compared to traditional flooding irrigation for almost all regions of Egypt (Table 6).

Table 6. Average blue water footprint (WF_{blue}) of onion under different irrigation systems for different regions of Egypt.

Region	WF_{blue} (m^3/ton)	
	Traditional flooding	Raised beds
Lower Egypt	227.3	172.4
Middle Egypt	250.0	196.1
Upper Egypt	263.2	227.3
Border governorates (Marsa Matrouh)	416.7	416.7
Average	277.8	227.3

Geries et al. (2021) probed the effect of DI on water productivity and yield. For an experiment at Kafr El-Sheikh Governorate on clay soils during two consecutive growing seasons, they applied three cut-off furrow irrigation strategies, at 90%, 80% and 70% of the strip length. They found a reduction in the blue unit water footprint of 7% (104 m^3/ton), 26% (84 m^3/ton), and 24% (86 m^3/ton), respectively, in comparison with the control situation where 100% of strip length is used (113 m^3/ton). They concluded that cut-off irrigation techniques can be considered effective interventions to save water, while maintaining yield levels and post-harvesting quality.

El-Metwally et al. (2022) tested the effects of deficit irrigation strategies in a surface drip system. For a two year experiment at El Beheira Governorate on sandy soil, they reported a blue unit water footprint of 90 m^3/ton when the onions received 100% of their crop water requirement. This unit water footprint dropped to 76 and 72 m^3/ton, respectively, when a 80% and a 60% deficit irrigation strategy was applied. However, a decline in yields was also observed, with reductions of 8% and 29% reported, respectively. Balancing water savings with yield losses, irrigating below 80% of the crop's water requirement is thus advised against.

A similar study has been carried out by Semida et al. (2020). For an experiment at Fayoum Governorate on sandy loam soil and under saline calcareous conditions, they tested the effect of four irrigation water strategies in a drip irrigation system, in which the onions received 120%, 100%, 80% and 60% of their crop water requirement, respectively. They found that blue unit water footprint can be reduced significantly under DI strategies, with the lowest value reported at 80% of crop water requirement (183 m^3/ton), compared to 242

m^3/ton for 100%, with a minor yield reductions (39.5 ton/ha vs 38.4 ton/ha for 100% and 80% respectively). Counterintuitively, however, the DI strategy of applying 120% of crop water requirements also resulted in a reduction of the blue unit water footprint (to 211 m^3/ton), largely driven by large increases in yield (to 50 ton/ha). This result can likely best be explained by the effect of soil salinity and the fact that the larger volumetric irrigation applications leached out salts out of the root zone, creating more favourable conditions for plant growth.

Due to its slow early growth and development, onion is a poor weed competitor. Adequate weed control is thus essential in onion production. El-Metwally at el. (2022) tested seven weed control practices, i.e. mulching with rice, wheat, and peanut straws, spraying the herbicides oxadiargyl and oxyfluorfen, mechanical weeding, and a case where non-active weeding took place. This latter case of non-active weeding yielded the largest unit water footprint at 142 m^3/ton. The smallest values were observed in the cases where mulches were applied, at 65-75 m^3/ton. The positive effect of mulching not only manifested in reducing weed pressure, but also in lowering the rate of water loss from the soil surface through evaporation and preserving soil moisture. Irrigation could therefore also be reduced by 20% (i.e. deficit irrigation at 80% of crop water use) against marginal yield losses.

For a two year experiment at Fayoum Governorate (sandy loam), Semida et al. (2020) tested the effect of applying proline foliar at 1 mM and 2 mM concentration. They found that the effect of proline foliar on unit water footprints was negligible in case it was applied to unstressed plants. However, when it was applied under a DI strategy, where the plant is subjected to water stress, blue unit water footprint could be reduced by over 20%. They concluded that a combination of a DI strategy at 80% of crop water requirements and application of 1−2 mM proline is recommended to attain decent yields while saving irrigation water over onion growing season.

A summary of the most effective measures in terms of unit water footprint reduction reported by the some of the cited literature is given in Table 7.

Table 7. Summary of the most effective measures to reduce unit water footprints (WF) over the control situation in onion production in the Egyptian context according to the consulted literature.

Reference	Location and soil type	Best strategy tested	Yield reduction	WF reduction
Ouda et al. (2021)	Different regions of Egypt (Upper, Middle and Lower Egypt). Traditional flooding and raised beds.	Raised beds (calculations based on statistics)	-	13% in Upper E. 21% in Middle E. 24% in Lower E.
Geries et al. (2021)	Kafr El-Sheikh Governorate (clay soil). Furrow irrigation.	Cut-off strategy – 80% of strip length	-13% (increase)	26%
Metwally et al. (2022)	El Beheira Governorate (sandy soil). SDI.	DI – 80% of ET during the whole growing season	8%	16%
Semida et al. (2020)	Fayoum Governorate (sandy loam). SDI with application of exogenous proline.	DI – 80% reduction (whole season) in combination with foliar application of 1−2 mM proline	3%	24%

Note: SDI is surface drip irrigation; DI is deficit irrigation.

TOMATO

The water footprint of tomato varies substantially, with global estimates reported above 650 m^3/ton for open field but poorly managed production conditions to below 5 m^3/ton for protected and excellently managed conditions (Nederhoff and Stanghellini, 2010).

In open field conditions, the most common approach to reduce the water footprint of tomato is through the deployment of drip irrigation, either surface or subsurface, where the latter is mainly deployed in light soils. For example, for an open field experiment at Behira Governorate on sandy soil, Kamal et al. (2013) evaluated the effect on unit water footprints of applying three different irrigation quantities through a drip irrigation system. They found that the smallest unit water footprint of 50 m^3/ton could be achieved by applying approximately 1800 m^3/fed (or 4476 m^3/ha). When they applied 2,400 m^3/fed (or 5714 m^3/ha) and 1,200 m^3/fed (or 2857 m^3/ha), respectively, resulting in unit water footprints of 62 m^3/ton and 53 m^3/ton.

For another open field experiment at El-Giza Governorate on sandy soil, Fawzy et al. (2019) tested the effect on unit water footprints of two drip irrigation systems. They found that SSDI reduced the blue water footprint by 8% compared to the SDI, with 19.5 and 21.2 m^3/ton, respectively.

In a comparable study to Fawzy et al. (2019), for an open field experiment at Kalyubia Governorate on loamy soil, Abdelhady et al. (2017) likewise found a unit water footprint reduction of 13% associated with SSDI compared to SDI (at 87 and 76 m^3/ton).

Beside the irrigation technology, the irrigation strategy chosen can also affect unit water footprints in open field tomato production, particularly deficit irrigation strategies. Based on an extensive literature review, Iqbal et al. (2020) concluded that although yields will be negatively affected by deficit irrigation strategies, the reduced cost of water and the increased quality of the achieved yield can offset economic losses.

Revisiting the aforementioned experiment by Fawzy et al. (2019), when testing various deficit irrigation strategies, they found that reducing the total water applied to 15, 30 and 45% of the crop water demand reduced the blue unit water footprints by 27, 29 and 36% (to 19.7, 19.1 and 17.4 m^3/ton) while suffering yield losses of 8, 10 and 24%, respectively.

Abdelhady et al. (2017) also reported on a field experiment carried out at Kalyubia Governorate (loamy soil), a reduction in unit water footprints by 7% when DI was applied at 80% of crop water demand through SSDI.

Studies on protected growing conditions, such as in greenhouses, in an Egyptian context are scarce. However, for a greenhouse experiment in agro-climatologically similar Saudi Arabia on sandy soil, Wahb-Allah et al. (2012) tested several deficit irrigation strategies at different crop growth stages. They reported a reduction in the unit water footprint by 12% (to 37.5 m^3/ton down from 44.1 m^3/ton under full irrigation) when the tomatoes were supplied with 75% of their crop water requirement. They moreover concluded that the fruiting and vegetative growth stages are the most tolerant to deficit irrigation strategies, while the reproductive stage is the most sensitive one.

For a similar greenhouse experiment at Saudi Arabia on loamy sandy soil, Alghamdi at al. (2023) concluded that when applying DI at 80% of crop water requirements, unit water footprints could be reduced by 10% at negligible effects on yields (20 kg/m^2 vs 19.3 kg/m^2 for 100% and 80% DI respectively).

While specific studies are few, growing tomatoes under protected conditions clearly offers multiple benefits that may reduce unit water footprints. First, protected settings allow producers to better control temperature and humidity, which can reduce transpiration and minimise the risks of pests and diseases. Moreover, low indoor wind speed and solar radiation in greenhouses can reduce evapotranspiration rates. In semi-arid Mediterranean regions, to which Egypt can be counted, Nikolaou et al. (2021) estimate that these rates can be reduced by 20 to 40%. Greenhouse settings also allow the reuse of drainage water, making production more circular in terms of both water and nutrients. The most advanced growing systems in protected conditions are closed hydroponic system in a closed greenhouse with advanced cooling. Such systems are reported to be able to reduce unit water footprints to values as low as 4 m^3/ton (Nederhoff and Stanghellini, 2010). Table 8 provides an overview blue unit water footprints of tomato under different types of greenhouse settings in various countries as provided by van Kooten et al. (2006).

Table 8. Blue water footprints (WF_{blue}) of tomato grown in various production systems. Source: (van Kooten et al., 2006).

Production method	Country	WF_{blue} (m^3/ton)
Open field	Various countries	100-300
Open field with drip irrigation	Israel	60
Unheated plastic greenhouse	Spain	40
Unheated glasshouse	Israel	30
Unheated plastic, regulated ventilation	Spain	27
Advanced controlled glasshouse with CO2 enrichment	Netherlands	22
Advanced controlled glasshouse with CO2 enrichment and closed hydroponic system	Netherlands	15
Closed greenhouse, with advanced controlled glasshouse with CO2 enrichment and closed hydroponic system	Netherlands	4

In a review study on water related parameters in greenhouse tomato production in semi-arid Mediterranean regions, Nikolaou et al. (2021) reported that the water footprint of tomato produced under greenhouse conditions in Egypt ranges from 58 m^3/ton in unheated greenhouses to less than 22 m^3/ton in greenhouses with a substrate culture. This latter value is slightly lower than similar unit water footprints reported for other semi-arid countries included in their study under the same conditions, i.e. 28, 43, 33, and 35 m^3/ton for Italy, Spain, Cyprus, and Greece, respectively. In general, the more closed and controlled the greenhouse system is, the lower unit water footprints are reported, although to the expense of a higher energy demand.

In their study to greenhouse operation and management in Egypt, El-Gayar et al. (2019), highlight the importance of irrigation scheduling in protected conditions. According to this author, considering the specificity of the micro-climate conditions, but also the possibility of using soilless media, vegetable production under greenhouse can save around 10% of the irrigation water applied. Other greenhouse management practices that can reduce unit water footprints reported include reducing the leaf area. By removing older leaves in tomatoes resulted in a 30% reduction in transpiration with no detrimental effect on crop yield.

Affecting both open field and protected growing conditions, the salinity of the irrigation water also has an impact on the unit water footprint. Both Wahb-Allah et al. (2012) and Alghamdi et al. (2023) found that despite the fact that tomato is considered a salt tolerant crop, using saline water for irrigation (i.e., at 3.6 dS m^{-1}) increases the water footprint by 20-25%, mostly due to a decline in yield. Likewise, Nikolaou et al. (2021) reported yield reductions of 10% and 25% when salinity was at 2.5 and 3.5 dS m^{-1}, respectively, thus increasing the unit water footprint.

A summary of the most effective measures in terms of unit water footprint reduction reported by the some of the cited literature is given in Table 9.

Table 9. Summary of the most effective measures to reduce unit water footprints (WF) over the control situation in tomato production in the Egyptian context according to the consulted literature.

Reference	Location and soil type	Best strategy tested	Yield reduction	WF reduction
Kamal et al. (2013)	El-Giza Governorate (sandy soil). SDI, with application of water saving substances (soil amendment)	1800 m^3 fed-1 combined with soil application of K-humate (2 kg fed-1 in every addition, 4 times during the season)	2%	16%
Fawzy et al. (2019)	El-Giza Governorate (sandy soil). SDI and SSDI.	DI – 85% of ET during the whole growing season, with subsurface drip irrigation	13%	35%
Abdelhady et al. (2017)	Kalyubia Governorate (loamy soi). SDI and SSDI.	DI – 80% of ET during the whole growing season, with subsurface drip irrigation	1%	19%
Wahb-Allah et al. (2012)	Saudi Arabia (sandy soil). Greenhouse with SDI.	DI – 75% of ET during vegetative growth stage or fruiting	2%	6%
Alghamdi et al. (2023)	Saudi Arabia (loamy sand soil). Greenhouse with SDI, with application of biochar as soil amendment.	DI – 80% of ET during the whole growing season, with no application of biochar.	2%	10%

Note: SDI is surface drip irrigation; DI is deficit irrigation.

LETTUCE

Compared to the previous crops, lettuce (and also strawberry) has relatively little coverage in literature.

For a two year trial at Assuit Governorate on sandy soil, Refai et al. (2019) assessed the effect of drought tolerance on lettuce unit water footprints. They applied three irrigation strategies of 100, 80 and 60% of crop water requirements, respectively, and found that blue unit water footprints were hardly affected by the reduction of irrigation supply. All strategies resulted in unit water footprints approximating 80 m^3/ton, since the reduction of water applied is unbalance by a reduction in yields, decreasing considerably by 20 and 30% for the 80 and 60% application rates, respectively. They also found that if the soil was protected with a plastic mulch—in the case of this experiment polyethylene black film and transparent polyethylene film—the reduction of direct evaporation from the soil increased yield while reducing the blue unit water footprint from 104 m^3/ton in uncovered soil to 60 and 75 m^3/ton in soil covered by black and transparent plastic, respectively.

For a two year experiment at Qalubia Governorate on clay soil, Ibrahim et al. (2023) tested the effect of foliar application of chitosan (at 150 ppm) and glycine betaine (at 700 ppm) on green lettuce. The experiment combined this application with two irrigation strategies, one well-watered strategy approximating full irrigation following the recommendation of the Egyptian Ministry of Agriculture (irrigation every 10–12 days) and a water stress inducing strategy that halved irrigation supply. In line with the findings of Refai et al. (2019), they found that blue unit water footprints remained relatively constant, while yields were drastically reduced. However, when Chitosan and Glycine betaine is applied under the DI strategy, the blue water footprint decrease, having a positive effects on crop production under water stress conditions.

STRAWBERRY

Strawberry is a water sensitive crop, both in terms of quantity and quality (particularly salinity). Moreover, production is highly sensitive to soil-borne diseases. Using alternative cultivated media such as soilless media can reduce the need of taking disease suppressing measures, such as fumigating the soil. Alternative media use is also associated with reduced production cost and beneficial indirect impacts on the environment and human health at large (Ahmed and Gad, 2022).

For an experiment under greenhouse conditions and using alternative substrate mixtures (i.e. perlite/peat and perlite/vermicompost) as soilless medium at El-Giza Governorate, Ahmed and Gad (2022) assessed the response of strawberry plants to various deficit irrigation strategies. They found that irrigating strawberry plants at 80% of their crop water requirement, combined with the use of a substrate of perlite and vermicompost (at a 3:2

ratio), resulted in the lowest unit water footprint of 86 m^3/ton—or 23% smaller than the average of 112 m^3/ton reported under other treatments.

For an experiment of two consecutive seasons at Qaluobia Governorate on clay soil, Ismail and Mubarak (2016) tested the effect on strawberry plant response of three irrigation strategies where water was applied at various intervals (i.e. once every two, three, and four days) through drip irrigation, while individually applying five different anti-transpirant foliar (i.e. potassium, sodium, aluminium silicate, magnesium, and calcium carbonate). They found that the use of anti-transpirants as foliar application can have a positive effect on yields, especially when a 75% DI strategy is applied, with unit water footprints of 150-160 m^3/ton reported against 200 m^3/ton in the control treatment with full irrigation and no foliar application.

6. BUSINESS OPPORTUNITIES

Opportunities are explored for Dutch businesses seeking to leverage Dutch expertise in smart water usage practices for Egyptian farmers implementing technical recommendations from the water footprint analysis. The overview below is created based on the previous experience of the authors as well as on input received from stakeholders during the consultation process. Note, therefore, that this list is non-exhaustive, and more opportunities will be available upon closer inspection.

Related to Production

- **Seeds and varieties**. Breed, trade, and grow high quality, drought-resistant, salt-tolerant, disease resistant, yield-increasing cultivars. As an added bonus, such varieties typically ease the application of deficit irrigation strategies and/or the application of irrigation water of lower water quality.
- **Measuring and monitoring.** Import and apply various types of sensors—both remote and on field—for measuring soil, water, climatological, weeds, pests, and nutrient conditions; various systems and software packages designed to help irrigation scheduling, fertilization, weeding, pest and disease management; Smart Water Monitoring and Management Systems to improve on-farm assessment of crop water demand and irrigation scheduling, based on a combination of weather(forecast), field data (soil and plant sensors) and remote sensing. This can be especially true in the case of localized systems or when crops are grown under greenhouse conditions; Soil testing and monitoring, for quickly and affordable assessment of soil nutrient status and development of fertilisation programs.
- **Technology and equipment.** Import and deploy machinery for planting, harvesting, cleaning, and soil management. Includes irrigation systems/technology.
    - Irrigation technology, either for design, capacity building and hardware provider, especially for technologies not currently widely available in the country (i.e. subsurface irrigation or control drainage).
    - Greenhouse design, construction and operation, to cope with the ambitious Egyptian plans for greenhouse expansion. Technical support is required to improve the local manufactory to produce devices, materials, soil-less media and supplies for modern greenhouses.
- **(Organic) Farming inputs.** Bio-stimulant and other related products to enhance crop growth and/or disease and drought resistance. Promotion and knowledge exchange for the local production of high-quality organic fertilisers.

Related to the value chain

- **Market forecasting systems**. Help farmers and agri-business understand the market and market dynamics so that they can grow the right crop for current market demand.
- **Cold chain technology**. Better storage and processing of produce to minimize food loss, especially cooled ones.

- **Shipping routes.** Ensure diversified and multiple shipping routes to gets crops to market (the absence of a direct Egypt-NL shipping route was mentioned as a relevant bottle neck during the interviews).
- **Alternative diets.** Promotion of less water-intensive and healthier diets, as well as increasing the local production of plant-based foods.

Facilitating opportunities

- **Training and capacity building.** Helping farmers best farming practices and skills tailored to the crops they are growing.
- **Labelling and certification.** Allow higher prices for e.g. organically grown produce. Acknowledgment of better water practices used. Transparency for consumers.
- **Agroforestry and other nature inclusive principles.** Produce more sustainable products.
- **Off-farm Water Decision Support Systems.** Desing and implementation of decision support systems to improve off-farm water management at the different levels (from the IWM districts to branch canal and mesqa), in order to align better water availability and demand, based on almost real-time crop water demand forecast. Crop water demand can be derived from field information and/or remote sensing technologies.
- **Water source or supply enhancement.** Desalination or treatment of source water for irrigation. Wastewater reuse techniques both for urban and drainage effluents.

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