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WAGENINGEN UNIVERSITY & RESEARCH

Horti Tech

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This study was carried out by Wageningen Social & Economic Research and was commissioned and financed by the Netherlands Enterprise Agency (Rijksdienst voor Ondernemend Nederland; RVO) and carried out by Wageningen Social & Economic Research (project number 2332200045).

Wageningen Social & Economic Research
Wageningen, June 2026

REPORT 2026-043

Ravensbergen, P., van der Salm, C., Hollaar, F., Splinter, G., van Adrichem, P. 2026. *Water use in greenhouses in North Africa: Model calculation of water-use efficiency and absolute water use in tomato production in greenhouse production areas.* Wageningen, Wageningen Social & Economic Research, Report 2026-043. 47 pp.; 3 fig.; 11 tab.; 32 ref.

This study investigates whether Dutch protected horticulture technologies in North Africa simultaneously improve water-use efficiency and reduce total water consumption, or instead lead to increased overall water demand due to production intensification.

The results illustrate a rebound effect consistent with the Jevons paradox: although technological intensification improves water-use efficiency ("more crop per drop"), total water consumption increases substantially ("more drops for more crop"). This increase is driven by higher yields per square metre (each kilogram of tomatoes contains approximately one litre of water), longer and more intensive cultivation, and additional water demand for cooling in climate control. The effect is strongest in desert regions, where cooling demand—especially from pad-and-fan systems—can dominate water use. In coastal areas, where cooling demand is met through misting, efficiency gains are more pronounced but still accompanied by higher absolute water consumption. The findings confirm that efficiency gains alone do not guarantee water savings and need to be supported by complementary governance and management measures.

The study combines a literature review, a greenhouse "stepping stone" model, and scenario-based simulations for coastal and desert production zones. Water and energy use were quantified across low-, mid-, and high-production systems, and results were validated through an expert workshop.

Keywords: horticulture, greenhouse, water-use efficiency, north Africa

This report can be downloaded for free at https://doi.org/10.18174/717994 or at http://www.wur.eu/social-and-economic-research (under Wageningen Social & Economic Research publications).

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Wageningen Social & Economic Research Report | Project code 2332200045

Cover photo: Jouke Campen

Contents

Preface

Freshwater is one of the most critical natural resources on Earth, underpinning both ecological integrity and agricultural productivity. Its availability is increasingly under strain, particularly in North Africa, owing to the combined effects of intensified freshwater abstraction and climate change. The latter is manifested not only in less precipitation but also in altered rainfall patterns, characterised by shorter, more intense precipitation events. Consequently, groundwater reserves are declining, while the frequency and severity of drought and the rate of soil salinisation are increasing.

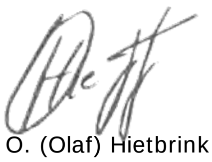
While certain plant species can physiologically and morphologically adapt to tolerate water deficit, others lack sufficient resilience and can be adversely affected by, or fail to survive, even short-term water shortages, in the order of several days. In controlled agricultural systems, such as greenhouse cultivation, the availability of consistently high-quality water is even more important, as both water quantity and quality directly influence plant growth, yield and system performance. In these systems, microclimatic conditions can be more extreme than in natural ecosystems, particularly with respect to temperature and relative humidity.

Dutch technology suppliers are world leaders in constructing and installing greenhouses, particularly when it comes to high-tech innovations in glass greenhouses. In North Africa, greenhouses are usually made of plastic and are less advanced. However, Dutch companies supply a large proportion of the water and climate control systems. These systems enable local growers to grow better produce, increase yield per square metre or achieve higher quality, all in a sustainable manner. Although Dutch horticultural technologies improve water-use efficiency, total water consumption may nevertheless increase as a result of production intensification.

The central challenge of this research lies in the lack of quantitative data and contextual insights into how Dutch greenhouse technologies affect both water-use efficiency and overall water demand. Current decision-making tends to focus on efficiency gains, often without fully accounting for net water use across different production systems, ranging from open-field cultivation to low-, mid- and high-tech greenhouse systems.

Water and energy use are only two of the broader impacts of greenhouse cultivation. Other relevant aspects — economic benefits for individual businesses and the wider region, job creation, innovation, the development of knowledge and education, the production and availability of healthy food at relatively affordable prices, landscape design and quality, and biodiversity — fall outside the scope of this study. The results should therefore be interpreted within this wider context and should not be used in isolation as an argument either in favour of or against greenhouse horticulture. An integrated perspective is required, in which advantages and disadvantages are assessed in relation to one another.

We thank the Netherlands Enterprise Agency (RVO), for making it possible for us to carry out this study. We also thank the experts who provided feedback on the interim results.



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Summary

S.1 Main research question

The Netherlands Enterprise Agency (Rijksdienst voor Ondernemend Nederland, RVO), in assignment with Ministry of Foreign Affairs, runs the so-called Combi-Tracks Programme. This programme promotes Dutch green and digital solutions as a means to achieve sustainable economic growth and strengthen sustainable trade in emerging markets.

A significant share of agri- and horticultural combi-tracks have been implemented in regions affected by water scarcity, making sustainable water management a critical concern. To address this, guidelines titled *Sustainable Water Use in Agri/Horti Combi-Tracks* have been developed. These guidelines highlight a key paradox: although Dutch horticultural technologies improve water-use efficiency ("more crop per drop"), total water consumption may nevertheless increase as a result of production intensification ("more drops for more crop").

The central challenge lies in the lack of quantitative data on, and contextual insights into, how Dutch greenhouse technologies affect both water-use efficiency and overall water demand. Current decision-making tends to focus on efficiency gains, often without fully accounting for net water use across different production systems, ranging from open-field cultivation to low-, mid-, and high-tech greenhouse systems.

The purpose of this project was to better understand how Dutch protected horticulture technologies contribute to both water-use efficiency and total water use in protected horticulture production sites in North Africa. While many Dutch innovations improve water-use efficiency, overall water consumption may still increase due to production intensification. The main research question was whether this assumption holds true. The study aimed to quantify water-use efficiency and total water use across different levels of horticulture technologies, and validate the findings with data and experts' judgements. As energy consumption correlates with water use, energy is included to a limited extent.

The target audience for this project consists of Dutch and North African horticulture industry stakeholders involved in protected horticulture, including policymakers, technology providers, growers and development partners working on the implementation of horticulture combi-tracks in water-scarce areas.

S.2 Messages

Water use in greenhouse tomato production in North Africa is not only related to irrigation, but is increasingly driven by climate control requirements

A substantial proportion of water is used for cooling purposes, particularly through fogging systems and pad-and-fan installations. Analysis of a fictitious North African case, consisting of a coastal production zone and an inland desert zone, demonstrates marked differences in water-use patterns. In coastal areas, irrigation remains the dominant component of total water use, while cooling demand is relatively limited due to milder climatic conditions and the applicability of fogging systems. By contrast, in desert regions, cooling water constitutes a substantial share of total water use in mid- and high-tech systems, becoming the dominant component in high-tech systems due to the necessity of pad-and-fan cooling and, in exceptional cases, air conditioning (airco).

Total water use (irrigation plus cooling) rises sharply with production intensity

Total water use (irrigation plus cooling) rises sharply with production intensity, averaging approximately 3,056 m³/ha in low-production systems, about 8,459 m³/ha in medium-production systems, and more than 40,746 m³/ha in high-production systems (see Tables S1 and S2). This is driven by higher yields per square metre (each kilogram of tomatoes contains approximately one litre of water), as well as increased water consumption for cooling in climate control and longer cultivation season. It is associated by higher-quality production in mid- and high-tech systems due to better climate control. In hot climates, cooling through pad-and-fan systems may account for more than 60% of total water use in mid- and high-tech systems. Airco systems in high-tech production systems can reduce water use to negligible levels when combined with drainage water recirculation and condensation recovery, but this comes at the cost of large investment and very high energy consumption. Across studies, irrigation water demand increased by approximately 143 m³/ha per additional kilogram of yield per square metre (excluding water use for cooling), highlighting the strong link between production intensification and water demand.

Table S1. Model calculation for a 10 ha company with low-, medium-, and high-production systems in a desert zone

Production system	Yield `000 kg	Water use – irrigation m³	Water use – cooling m³	Water use – irrigation + cooling m³	Water efficiency L/kg	Energy use MWh
Low-production	480	30,560	0	30,560	63.7	300
Medium-production	2,118	77,010	7,580	84,590	39.9	1,200
High-production, no airco	7,200	140,400	267,060	407,460	56.6	3,300
High-production, airco	7,200	140,000	-120,000	20,000	2.8	58,000

Table S2. Model calculation for a 10 ha company with low-, medium-, and high-production systems in a coastal zone

Production system	Yield `000 kg	Water use – irrigation m³	Water use – cooling m³	Water use – irrigation + cooling m³	Water efficiency L/kg	Energy use MWh
Low-production	480	30,560	0	30,560	63.7	300
Medium-production	2,118	77,010	3,000	80,010	37.8	1,200
High-production, fogging	7,200	140,400	90,000	230,400	32.0	2,000

Take-aways from the model calculations for a 10 ha company are:

- **Increasing production of tomato per square metre in greenhouses in North Africa through further technological intensification increases absolute water use but also use efficiency**
  Further technological intensification towards higher-production systems generally leads to greater efficiency. For water use, this efficiency is most evident in the transition to high-production systems in the coastal zone, where fogging is applied for cooling. Although fogging increases absolute water use, this is offset by a proportionally larger increase in tomato production of 48, 212, and 720 tonnes per hectare for low-, medium-, and high-production systems, respectively. Absolute water use amounts to 3,056, 8,001, and 23,040 m³ per hectare. Consequently, water-use efficiency improves markedly to 63.7, 37.8, and 32.0 litres per kilogram of yield, respectively.

- **Water-use efficiency barely improves in the desert zone when production system levels increase and pad-and-fan systems are applied**
  In the desert zone, cooling in high-production systems relies primarily on pad-and-fan systems, which consume substantial volumes of water. Absolute water use rises sharply to 3,056, 8,459, and 40,746 m³ per hectare for low-, medium-, and high-production systems (excluding airco). Although production levels are comparable to those in the coastal zone, water-use efficiency improves for medium production, however only marginally for high-production, with values of 63.7, 39.9, and 56.6 litres per kilogram of yield.

- **Air conditioning is an extremely water-efficient cooling instrument, but is economically and energetically challenging**
  Water-use efficiency within the desert zone is extremely high when airco is used (2.8 litres per kilogram of yield), owing to near-complete recirculation of irrigation water. However, this option requires highly advanced greenhouse technology and substantial capital investment, limiting economic feasibility to exceptional cases. Moreover, energy use is extremely high.

- **Absolute water use increases substantially when production systems and technology develop to higher levels**
  Shifting from a low- to a high-production system substantially increases absolute water use in both zones. Water use per hectare is more than thirteen times higher in high-production systems in the desert zone, and seven and a half times higher in the coastal zone, than in low-production systems.

Absolute water consumption increases significantly with higher production levels
Model simulations show that absolute water consumption increases significantly when production systems in a 1,000 ha area of tomato shift from low to high through technological intensification, despite improvements in water-use efficiency per unit of output (see Tables S3 and S4). This rebound effect is consistent with the Jevons paradox, which posits that efficiency gains in resource use do not necessarily lead to lower overall consumption and may, in fact, result in greater use. The report illustrates this rebound effect through scenario modelling, rather than providing direct empirical evidence for greenhouse horticulture. However, this phenomenon has been empirically observed in multiple studies on irrigation in agricultural systems.

Table S3. Model calculation of a desert horticultural area of 1,000 ha tomato (baseline) introducing medium- and high-production systems (with pad-and-fan systems, no airco)

Production system	Yield tonnes	Water use m^3	Water efficiency L/kg	Energy use MWh	Land used for horticulture ha
Baseline: 60% low; 30% medium; 10% high	164,340	8,058,440	49.0	141,700	1,000
Scenario 1: Increased production — 40% low; 45% medium; 15% high	222,510	10,753,390	48.3	170,200	1,000
Scenario 2: Stable production, reduced area — 40% low; 45% medium; 15% high	164,340	7,942,169	48.3	125,705	739
Scenario 3: Increase in area — 40% low; 45% medium; 15% high	244,761	11,828,729	48.3	187,220	1,100

Table S4. Model calculation of a coastal horticultural area of 1,000 ha tomato (baseline) introducing medium- and high-production systems

Production system	Yield tonnes	Water use m^3	Water efficiency L/kg	Energy use MWh	Land used for horticulture ha
Baseline: 60% low; 30% medium; 10% high	164,340	6,537,900	39.8	74,000	1,000
Scenario 1: Increased production — 40% low; 45% medium; 15% high	222,510	8,278,850	37.2	96,000	1,000
Scenario 2: Stable production, reduced area — 40% low; 45% medium; 15% high	164,340	6,114,540	37.2	70,903	739
Scenario 3: Increase in area — 40% low; 45% medium; 15% high	244,761	9,106,735	37.2	105,600	1,100

Take-aways from the model calculations of a horticultural area introducing medium- and high-production systems are:

- Implementing a higher-production system results in greater total water use
  Implementation of a higher-production system increases yield by 35% for the same cultivation area. The greater yield is accompanied by increases in total water use of 27% in the coastal zone and 33% in the desert zone.

- Implementing a higher-**production system leads to substantial land sparing when the cluster's** tomato output remains constant
  A higher-production system increases output per unit area. If production remains constant, the required greenhouse area can be reduced by up to 26% in both desert and coastal zones.

- Increasing the size of the production area combined with implementing a higher-production system leads to a particularly large increase in absolute water use
  When the technology level of the production system improves and the greenhouse area increases by 10%, absolute water use rises substantially: by 39% in the coastal zone and 47% in the desert zone.

- Energy use is an important trade-off when selecting cooling technology
  Energy consumption is largely determined by the cooling technology applied and is therefore a critical factor in economic and operational decisions. Electricity availability and cost are key constraints. Pad-and-fan systems, and especially airco in desert high-production systems, result in high to extremely high energy use: about 330 MWh and 5,800 MWh per hectare, respectively.

Message for technology suppliers
These findings are particularly relevant in regions where water resources are scarce. For Dutch technology suppliers, this implies the need to communicate a more comprehensive value proposition: while water-efficient technologies can reduce unit water use, they may also contribute to increasing total water demand unless accompanied by complementary measures. Such measures may include early adoption of drainage water recirculation, alternative water sourcing strategies, or solutions that reduce dependence on groundwater and surface water. Continuous measurement and monitoring salinity/EC, groundwater levels, well depth, source-water mix, drainage discharge, return flows, total water use and water efficiency by greenhouse entrepreneurs are essential to evaluate long-term water-resource sustainability.

Message for policy makers
For policymakers, the results underscore that promoting efficiency-enhancing technologies alone is unlikely to be sufficient. Instead, complementary governance instruments are required to address absolute water use on a regional scale. Such instruments may include the development of water area management plans, in which clear norms, allocation rules, and usage limits are established for both groundwater and surface water, as well as for different categories of users through permitting or licensing systems.

Policy instruments may further include mandatory requirements related to, for example, rainwater harvesting per hectare, incentives or obligations for the use of alternative water sources such as desalinated seawater, and restrictions on groundwater abstraction in water-stressed regions. Innovation and knowledge development and transfer programmes could support policy interventions. These measures can help ensure that efficiency gains translate into less pressure on local water resources.

Continuous measurement and monitoring are essential to evaluate the real-world effects of technological upgrades and policy interventions. This includes monitoring groundwater abstraction volumes, groundwater levels, and water quality parameters at the area level. Such monitoring will enable authorities to detect unintended effects at an early stage and adjust policy instruments accordingly.

Message for relevant stakeholders: public—private partnerships

Effective water governance in greenhouse horticultural areas requires close collaboration between the private sector, public authorities, and knowledge institutions. Joint monitoring programmes, data sharing, and applied research can support evidence-based decision-making and help align technological innovation with long-term water sustainability objectives.

Recommendations

Based on the findings and conclusions of this study, the following recommendations are proposed:

1. *Undertake a comprehensive integrated assessment of greenhouse development*
   A comprehensive assessment is required to determine whether greenhouse intensification is appropriate in the local context. The assessment should consider socio and economic and environmental costs and benefits, and pressures on natural resources (water, energy, land, biodiversity) to identify trade-offs and to justify public investment.

2. *Collect empirical data for water-efficient greenhouse systems*
   Future production system intensification should explicitly consider water use (efficiency and total use). Technology choices must be justified and supported by empirical data from practice, including key conditions such as monitoring and abstraction limits. Reliable real-world data remain limited.

3. *Unlock water efficiency gains through targeted management interventions*
   Water management is critical. Efficiency gains can be achieved through irrigation control, recirculation, and monitoring, and these can be 'quick wins'. However, without regulation, these do not guarantee absolute water savings. Targeted programmes are needed.

4. *Align policies with regional water availability*
   Efficiency improvements alone do not reduce total water use. Policymakers should implement water governance measures to prevent uncontrolled growth in water abstraction, as well as sound spatial planning. Measures should include area-based water allocation limits or conditional permitting to align development with regional water availability.

5. *Analyse land sparing-related benefits and trade-offs*
   Intensification may contribute to land sparing if properly governed, potentially freeing land for other uses. Further analysis is required to ensure the most efficient use of land, while considering the impacts associated with land-sparing.

6. *Foster a clearer and stronger connection between the water user (greenhouse) and the water system*
   The link between water demand and regional availability, hydrological limits, and basin impacts has not been sufficiently analysed. As a result, production system compatibility with the water system's carrying capacity remains unclear. Stronger integration is required.

7. *Further explore alternative optimisation strategies, rather than approaches predominantly driven by technological solutions*
   This analysis is mainly technological, and excludes alternative strategies such as crop choice, seasonality and spatial planning. Further research should seek to strengthen the link between water use, water availability, and system limits.

8. *Undertake an environmental assessment of seawater desalination*
   Further research into the environmental impacts of seawater desalination, including energy use, brine disposal, and ecosystem effects, is required before this strategy can be considered sustainable.

S.3 Methodology

The following activities have been implemented:

1. *Overview of Dutch technologies and 'stepping-stone' scenarios for investment in protected horticulture*
   The stepping-stone model, originally developed by Dutch technology supplier Priva, outlines nine stages to transition from open-field cultivation to high-tech horticulture, including intermediate phases. This model has been updated and expanded with current data and insights.

2. *Literature review on water and energy use in tomato cultivation*
   A comprehensive literature review was conducted on water and energy consumption in tomato production (across various cultivars) under different greenhouse types in North Africa (Morocco, Tunisia, Egypt). Relevant literature from Southern Europe (Spain, Italy, Turkey) and the Middle East (Jordan, Saudi Arabia) was also included due to comparable climatic conditions. The findings have been systematically compiled in a Microsoft Excel database, including variables such as crop type, greenhouse technological level, yield per square metre, water use per square metre (for irrigation and, where available, cooling), water consumption per hectare, and energy use per square metre.

3. *Scenario analysis based on representative production areas*
   Based on research into horticultural regions in Morocco, Tunisia, and Egypt, two fictitious 1,000 ha areas of tomato production were defined (baseline scenario): one coastal zone and one inland desert zone. For these zones, three scenarios were analysed:
   a. Increased technological intensification: In this scenario, the area under low-productivity systems decreased by 33.3%, while the area under medium- and high-productivity systems each increased by 50%. The impacts on water and energy consumption were assessed.
   b. Constant production with technological intensification: In this scenario, production levels remained constant while technological intensification followed Scenario 1. The resulting reduction in cultivated area and associated water use were evaluated.
   c. Area expansion: In this scenario, the cultivated area increased by 10% and the resulting impacts were analysed, applying the same assumptions as in Scenario 1.

4. *Expert validation*
   The findings and proposed scenarios were reviewed in an expert workshop. Feedback and recommendations from two Wageningen University & Research experts and two experts from companies with experience in North Africa were incorporated into the subsequent analysis.

5. *Reporting*
   The results were documented in a comprehensive report.

1 Introduction

1.1 Motivation for the study

The availability of good-quality water in greenhouses is crucial. Without water, plants will die quickly, not only because they cannot obtain water naturally — such as through rainfall — but also because the environmental conditions in greenhouses are sometimes more extreme than those found in nature, particularly in terms of temperature and humidity.

Dutch technical suppliers are world leaders in the construction and installation of greenhouses, particularly when it comes to high-tech innovations in glass greenhouses. In North Africa, greenhouses are usually made of plastic and are less advanced. However, Dutch companies supply a large proportion of the water and climate control systems. These systems enable local growers to produce better produce, increase yield per square metre, or achieve higher quality, all in a sustainable manner.

The Netherlands Enterprise Agency (Rijksdienst voor Ondernemend Nederland, RVO), in assignment with Ministry of Foreign Affairs, runs the Combi-Tracks Programme.[1] This programme promotes Dutch green and digital solutions to address local challenges in emerging markets. Active in 14 countries across Africa, Asia, and South America, it brings together government institutions, knowledge organisations, civil society, entrepreneurs and local stakeholders. Through this integrated approach, the programme seeks to stimulate local economic development, generate meaningful employment, and strengthen Dutch exports and investments, while supporting the transition towards green and digital economies.

The Combi-Tracks Programme focuses on sectors where Dutch expertise offers clear added value, addressing social and environmental challenges related to sustainability and digitalisation. The model is built on mutual benefit: Dutch companies enhance their international competitiveness, while host countries benefit from innovative solutions and improved economic resilience. Implementation is coordinated through close collaboration between embassies, Invest International, and RVO, ensuring effective resource allocation and capacity building to improve local business environments and attract Dutch trade and investment.

A significant share of agri- and horticultural combi-tracks have been implemented in regions affected by water scarcity, making sustainable water management a critical concern. To address this, guidelines titled *Sustainable Water Use in Agri/Horti Combi-Tracks* have been developed. These guidelines highlight a key paradox: although Dutch horticultural technologies improve water-use efficiency ("more crop per drop"), total water consumption may nevertheless increase as a result of production intensification ("more drops for more crop").

1.2 Main research question

The main challenge this project sought to address is the lack of quantitative data and contextual understanding on how Dutch greenhouse technologies contribute to both water-use efficiency and total water use in practice. Current decision-making and policy design often focus on efficiency gains, without accounting for the net effect on total water demand at different technological levels (open-field, low-tech, mid-tech, and high-tech greenhouse production systems).

This project aimed to fill that gap by developing quantified scenarios that illustrate water-use efficiency and total water use across different implementation situations of Dutch technologies in greenhouses.

[1] Overview of Combi-Tracks: doing business with impact in emerging markets | RVO.nl

1.3 Objectives

The purpose of this project was to better understand how Dutch protected horticulture technologies contribute to both water-use efficiency and total water use in protected horticulture production sites in North Africa. While many Dutch innovations improve water-use efficiency, overall water consumption may still increase due to production intensification. The study aimed to quantify water-use efficiency and total water use across different levels of horticulture technologies, and validate the findings with data and experts' judgements.

Since possible trade-offs exist between different environmental pressures (e.g. water and energy use), a second objective was to gain more insight into the efficient use of energy, and total energy use in horticulture production using different sets of technologies.

Important note and disclaimer

This study focuses on the impact of technological development and the resulting intensification of cultivation on water use, both in terms of efficiency and absolute consumption. Energy use is also considered, albeit indirectly. To the best of our knowledge, there has been no previous study specifically examining the effects of technological intensification on water use in greenhouse horticulture. As such, this research provides new insights into this particular field and represents a valuable contribution for entrepreneurs, knowledge professionals and policymakers alike.

However, water and energy use are just two broader impacts of greenhouse cultivation. Other relevant aspects — economic benefits for individual businesses and the wider region, job creation, innovation, the development of knowledge and education, the production and availability of healthy food at relatively affordable prices, landscape design and quality, and biodiversity — fall outside the scope of this study. The results should therefore be interpreted within this wider context and should not be used in isolation as an argument either in favour of or against greenhouse horticulture. An integrated perspective is required, in which the advantages and disadvantages are assessed in relation to one another.

1.4 Target audience

The target audience for this project consists of Dutch and local horticulture industry stakeholders involved in protected horticulture, including policymakers, technology providers, growers and development partners working on the implementation of horticulture combi-tracks in water-scarce areas.

1.5 Intended outcomes and deliverables

The intended outcomes of this project include:

- Insight into 'stepping stones', i.e. the technological stages along an investment pathway to progress from open-field production to low-, mid- and high-tech greenhouse production systems.
- Insight into existing technologies used in horticulture in North Africa that will likely be upgraded or replaced by more advanced Dutch technologies.
- Quantification of water-use efficiency and total water consumption in horticultural production in North Africa, based on the application and replacement of different technology sets, including quantification of efficiency assessments related to the use of energy.
- Conclusions and recommendations: interpretation of the results and reflection on how different technology sets contribute to mitigating environmental pressures. This includes assessment of the impact of company-level technology choices on entire (horticultural) regions, and identification of measures and considerations required at the landscape level.

The results, conclusions and recommendations are described in this report and an accompanying Microsoft PowerPoint presentation.

1.6 Reading guide

The report begins with a summary. Chapter 1 describes the background, problem statement, objectives, scope, and intended results. Chapter 2 describes the methodology. Chapter 3 presents the results: Section 3.1 describes the stepping stones while Section 3.2 describes water and energy consumption based on the literature. These are followed by descriptions of two fictitious clusters of horticultural greenhouses, in Section 3.3. The model calculations based on three scenarios are presented in Section 3.4. Chapter 4 discusses the findings and outlines conclusions. Finally, recommendations are set out in Chapter 5.

2 Methodology

2.1 Introduction

The methodology comprised the following activities, which address the research questions and contribute to the intended outcomes:

1. Overview of technologies and investment pathways: An overview of Dutch technologies was compiled and step-by-step investment scenarios for protected horticulture were developed. This resulted in a stepping-stone model consisting of nine stages, ranging from open-field cultivation to high-tech horticulture, including all intermediate phases.

2. Literature review: Existing literature on water and energy consumption associated with the cultivation of a single tomato crop in different types of greenhouses in North Africa was reviewed. Because of comparable climatic conditions, studies focusing on the Mediterranean, Middle East, Gulf region and Southern Europe were taken into account.

3. Baseline scenario development: A fictitious country scenario (the Azuria baseline scenario), featuring two horticultural clusters within the region, was developed based on research into horticultural regions in North Africa. One cluster was located in a coastal area, while the other was in an inland desert-like environment.

4. Model calculations: Calculations were based on three scenarios:
   a. A shift towards further production system technological intensification within the clusters
   b. The same shift within the clusters, but with total production volumes remaining constant
   c. A 10% increase of the total cultivated area while maintaining the same distribution of production systems as in scenarios (a) and (b).

5. Expert session: The findings, scenario assumptions and outcomes were reviewed and tested during an expert session. The insights and recommendations provided by the experts were incorporated into the analysis.

6. Reporting

The activities are described in more detail in the sections below.

2.2 Stepping-stone model

This study adopts the stepping-stone model, originally developed by Priva in 2012 (Priva, personal communication, 2026) as a conceptual starting point for structuring the differences between protected horticulture systems. The original model distinguishes nine levels, which describe typical combinations of greenhouse construction, climate control, irrigation system, cultivation system, and management characteristics.

For the purposes of this report, these nine levels are not applied directly as the primary analytical categories. Instead, production systems are grouped into three broader categories based on production intensity: low-, medium-, and high-production systems. This approach was chosen because, in practice, considerable variation in productivity exists within greenhouse systems that would otherwise be classified as low-, mid- or high-tech. Such variation is influenced not only by the level of technology applied, but also by management practices and the specific combinations of technologies implemented at the company level.

The stepping-stone model is therefore used as a descriptive framework to identify relevant system characteristics, while the comparative analysis in this report is based on production technology level. In practice, companies frequently combine elements from multiple stepping-stone levels within a single production system. Consequently, the stepping stones are treated as archetypal system configurations rather than as fixed or discrete company types.

Within this framework, the analysis focuses specifically on water-related system characteristics, with particular attention to irrigation water and water used for climate control (cooling). The model serves to support a structured comparison between low-, medium-, and high-production systems, and to position water use within the wider configuration of production systems.

2.3 Water and energy use in literature

Publication databases (CAB Abstracts, Google Scholar) were searched to obtain an overview of data on water and energy use in tomato cultivation in greenhouses in North Africa, the Middle East and the Mediterranean.

Search terms used included, among others, water use, water-use efficiency (WUE), and greenhouses in combination with the region of interest (North Africa, Middle East, Mediterranean or specific countries). This led to more than 50 relevant papers.

Tomatoes were selected as the focus crop because they are one of the dominant greenhouse crops in North Africa and offer the most consistent and available data on yields, water use and technology. Their strong sensitivity to climate and management also makes them a suitable reference crop for analysing the key dynamics of greenhouse systems, while keeping the scenario analytically manageable.

Data from the Middle East and Mediterranean were used alongside data from North Africa, as climate conditions are quite similar. Inclusion of these data extended the dataset considerably.

The papers were further screened for the presence of relevant data and the length of the cultivation period. This led to a subset of 15 papers. From these papers, data were selected based on the type of greenhouse and equipment involved (greenhouse construction, climate control system, irrigation system), and on yield, product water use (L/kg), and/or areal water use (m^3/ha) and energy use. Where possible, data were split into water use for irrigation and for cooling.

The data were then grouped to low-, medium-, and high-production, and averages and median values for water and energy use were calculated. We decided to differentiate by production level instead of stepping stone as we experienced large variation in productivity within low- (0–10 kg/m^2), mid- (10–40 kg/m^2) and high-tech (> 40 kg/m^2) systems. These differences can be explained by management as well as by the exact combinations of technologies (construction, climate control, irrigation system). For each production level, both average and median values were calculated.

2.4 Composition of a horticultural cluster

In this report, a fictitious country scenario (the Azuria baseline scenario) is presented, featuring two horticultural clusters located in North Africa. The first cluster is in a desert zone, while the second is in a coastal environment. The description of this country and its two horticultural clusters was developed by comparing information from several countries and distilling the most relevant shared patterns. Identified similarities in climate, water use and cultivation practices were consolidated into a single fictitious reference country, which served as the basis for further analysis.

This approach is grounded in reports and selected websites relating to greenhouse horticulture and water contexts in Morocco, Tunisia, Egypt, and Algeria. These sources were complemented by a literature review focusing on water use, energy consumption and yield indicators in tomato cultivation within North African and Mediterranean climate zones. International sources, such as Food and Agriculture Organization of the United Nations reports and sector studies, formed the basis for general knowledge on greenhouse technology, water use and tomato production in Mediterranean and arid climates. These sources provided insight into fundamental relationships, such as crop water requirements, irrigation systems, and climate control in greenhouses.

The country-specific details are based on national and regional studies. For the coastal context, information from Morocco in particular was used, where groundwater use, export-oriented production and mid-tech greenhouse concepts are dominant. Egypt provided the key reference for large-scale desert agriculture, with an emphasis on high-tech systems, the use of fossil groundwater, and intensive climate control. Tunisia complemented this picture with insights into water scarcity, transitions to more efficient irrigation systems, and variation in technology use. Finally, Algeria offered a clear picture of the role of low-tech tunnels and the rapid scaling-up of greenhouse horticulture in arid areas.

Together, the sources represent the three core layers of information on which the Azuria scenario is based:

1. Scientific literature → yields, water use, technological impacts
2. International reports (FAO, World Bank, RVO) → water availability, policy context, sector structure
3. Practical and sector information → greenhouse types, business structures, logistics and markets.

In the first step, the selected countries were analysed individually across a number of key themes, including agro-climatic conditions, water availability and water sources, applied production systems (low-, medium and high-producing systems), irrigation and cooling strategies, greenhouse technologies, tomato productivity, the profile of entrepreneurs, and the role of logistics and knowledge infrastructure. These analyses were based on a combination of existing country studies, technical reports, practical case descriptions and thematic background sources.

In the second step, recurring patterns and structural similarities between the four countries were identified. Attention was given to differences between desert and coastal production zones, because of the ways in which climate and water availability influence technology and production system choices. Country-specific details were not transferred directly but were instead interpreted functionally; the objective was not to reconstruct an actual country.

In the third step, these patterns were abstracted and integrated into a fictitious reference country, Azuria, with clearly delineated regions. The desert and coastal zones in Azuria are therefore not replicas of existing regions, but conceptual representations of the characteristic conditions found across North Africa.
The selected distributions of production systems, yield levels, and water use are explicitly intended as starting points for scenario development, rather than as forecasts or policy recommendations.

This process resulted in a baseline (0) scenario that can be used for further modelling and to compare alternative development pathways. In parallel with the country analysis, a literature review was conducted to compile available quantitative data on water and energy use in greenhouse tomato production (see Section 2.3). These data were used as inputs for the baseline scenario.

The resulting scenario developed through this approach does not represent individual case studies, but rather standardised, literature-based reference values that can be compared across production systems and climate zones. Azuria thus functions as an analytical framework for the assessments presented in this report.

2.5 Model calculations based on scenarios

To better understand the implications of water use associated with the transition towards higher-level production systems in North African horticulture, this study applied a set of scenarios representing different technological development pathways.

As described in Section 2.4, two climatic zones were distinguished for the fictitious North African country of Azuria: a desert zone and a coastal zone. For both zones, a baseline (0) scenario was defined as a starting point and reference, consisting of a horticultural cluster of 1,000 ha of tomato cultivation. Within each cluster, the cultivated area was distributed across three production systems — low-production, medium-production and high-production — covering 600, 300 and 100 ha (i.e. 60%, 30% and 10%), respectively. This distribution of production systems across the cultivated area is based on insights obtained during the expert session on the current levels of applied horticultural technologies and production systems in North Africa, and is considered a representative reflection of the sector in this region.

For both zones, analyses were carried out per production system to assess yields in kilograms of product and water use per hectare and per square metre, as well as water and energy use per kilogram of product.

Building on this baseline, scenarios were developed to explore shifts between systems within the clusters. Scenario 1 assumes that the total cluster area remains constant at 1,000 ha, while the allocation of land across production systems changes relative to the baseline. In this scenario, the area under low-producing systems decreases from 60 to 40%, while the area under medium-producing systems increases from 30 to 45%, and under high-producing systems from 10 to 15%, resulting in areas of 400, 450 and 150 ha, respectively. For Scenario 1, production levels and water use were subsequently analysed.

Scenario 2 applies the same proportional redistribution of land across production systems as in Scenario 1 (40%, 45%, and 15%, respectively) but assumes that the production output of the cluster remains constant. In this scenario, the total cultivated area decreases due to higher productivity associated with the shift towards more intensive systems. Scenario 2 thus represents a situation in which there is no need for additional production in absolute terms, and the same production volume as in the baseline scenario is achieved on less land.

Scenario 3 assumes a 10% increase in total cultivated area, while maintaining the same distribution across production systems as in Scenarios 1 and 2. This scenario simulates a situation in which the transition towards higher production levels stimulates the expansion of the horticultural area within the cluster.

2.5.1 Elaboration of the scenarios

Baseline scenario (0)

Allocation of the cultivated area for the baseline (0) scenario and scenarios 1, 2, and 3 is based on a realistic representation of the development of greenhouse horticulture clusters in countries comparable to Azuria. In Section 3.3, these horticultural clusters are described in greater detail.

Global knowledge exchange in the fields of horticultural technology, plant science, and agribusiness management drives the technological intensification of activities in such regions. In many cases, this process is accompanied by the establishment of production sites by internationally operating horticultural companies, for example those originating from the Netherlands.

In countries such as Azuria, the tomato-growing season extends into winter, a period during which cultivation in the Netherlands is climatically constrained or not feasible without artificial lighting. Winter production in these regions enables internationally operating companies to ensure year-round supply to their markets.

Scenario 1

A development trajectory for tomato production clusters in Azuria in which, within a total production area of 1,000 ha, the area under medium-production systems increases from 300 to 450 ha, and under high-production systems from 100 to 150 ha, is considered plausible.

The timeframe required to implement this scenario is difficult to determine with precision. Data on greenhouse area across low-, medium-, and high-production systems over time have not been systematically recorded, and corresponding growth rates are therefore unavailable. Expert estimates suggest that the total greenhouse area in North Africa has expanded at 3–5% per annum. The technological transition itself typically proceeds at a slower pace than overall area expansion, but follows a similar trajectory, and may be estimated at 2–4% per annum.

Under these assumptions, an increase in the area under medium-production systems from 300 to 450 ha, and under high-production systems from 100 to 150 ha (representing a 50% increase in both cases), would correspond to a timeframe of approximately 12–20 years. It should be noted, however, that the transition from low- to mid-tech systems is largely driven by local growers, for whom these estimates are likely to be realistic. In contrast, the transition to high-tech systems may proceed more rapidly, as greater access to investment capital enables larger and more concentrated area developments. Although difficult to predict with certainty, an increase of approximately 50 ha in high-production systems could plausibly be achieved within a period of about five years.

Scenario 2

The distribution of cultivated area across low-, medium-, and high-production systems in Scenario 2 is identical to that in Scenario 1, and is likewise based on a realistic representation of greenhouse cluster development in countries comparable to Azuria. As described in Section 3.3, these patterns reflect processes of further technological intensification driven by international knowledge exchange.

In contrast to Scenario 1, Scenario 2 assumes that total tomato production remains equal to that of the baseline scenario. Consequently, the higher productivity associated with more land under medium- and high-production systems results in a reduction in the cultivated area required to achieve the same output.

Under this scenario, production intensification leads to more efficient land use, as fewer hectares are required to produce an equivalent volume of tomatoes. This reflects a situation in which technological advancement and improved management practices are primarily directed towards optimising resource efficiency, rather than expanding total production.

The timeframe for this transition is assumed to be the same as in Scenario 1.

Scenario 3

The allocation of cultivated area across low-, medium-, and high-production systems in Scenario 3 follows the same pattern as in Scenarios 1 and 2, reflecting a realistic development of greenhouse clusters in countries comparable to Azuria. As described in Section 3.3, these developments are driven by global knowledge exchange and are often supported by internationally operating firms.

In contrast to Scenario 2, Scenario 3 assumes that technological intensification creates an attractive investment climate, thereby stimulating further expansion of greenhouse production. Rather than maintaining or reducing the cultivated area, the cluster experiences growth driven by improved efficiency, higher productivity, and increased competitiveness of medium- and high-production systems. Under this scenario, the total greenhouse area increases by 10%, from 1,000 to 1,100 ha. This reflects a pull effect of technological intensification, whereby technological progress not only enhances productivity but also induces structural expansion of the sector.

Regarding the timeframe, two dynamics should be clearly distinguished: expansion of total cultivated area and further technological intensification. In line with Scenario 1, technological intensification would take 12-20 years. By contrast, expansion of greenhouse area would occur over a much shorter period of 2-3 years. It can reasonably be assumed that this growth will be predominantly realised through expansion of mid- and high-tech production systems.

2.6 Expert session

On 2 April 2026, an expert session was held to review the underlying assumptions and model calculations. In addition to the project team and the client, the session involved two experts from Wageningen University & Research (WUR) and two industry experts with practical experience in North Africa.

As a result of this session, three key adjustments were made. First, the classification was revised to focus on low-, medium-, and high-production systems, rather than low-, mid-, and high-tech systems.
As outlined in Section 2.2, this approach was chosen because, in practice, considerable variation in productivity exists within greenhouse systems that would otherwise be classified as low-, mid- or high-tech. Such variation is influenced not only by the level of technology applied, but also by management practices and the specific combinations of technologies implemented at the company level, which do not necessarily fit into a single 'stepping stone' but are spread across several stepping stones.

Second, a third scenario was introduced: a growth scenario involving a 10% increase in the cultivated area. The reason for this is that the acreage of greenhouses in the North Africa region is growing.

Third, supplementary data were provided on water use for climate control, including misting, pad-and-fan, and air-conditioning (airco) systems, as well as on the associated increase in energy consumption resulting from intensification to higher levels of production.

2.7 Reporting

The results of the above activities have been included in this report. In addition, a brief Microsoft PowerPoint presentation was produced that sets out the conclusions.

3 Results

3.1 Stepping stones

The stepping stone matrix provides an overview of the range of protected horticulture systems relevant to tomato production in North Africa. The original matrix distinguishes nine levels, representing different combinations of greenhouse construction, irrigation, climate control, cultivation system, and management characteristics. Together, these levels illustrate the diversity of production systems, ranging from relatively simple and low-input systems to more intensive systems with higher levels of control and management (see Table 1).

Analysis of the stepping stones shows that these levels cannot be interpreted as fixed company types. In practice, companies combine different technological and managerial elements within one production system. For example, relatively simple greenhouse structures may be combined with more advanced irrigation or cooling techniques, while more advanced greenhouse systems may still apply relatively simple water management. This means that the stepping stones are most useful as archetypical system configurations that help to structure variation, rather than as exact categories into which individual companies can be placed.

A second result from the stepping stone analysis is that differences between systems are not only technological, but also strongly related to productivity. Although the nine levels suggest an overall progression in system intensity, productivity varies substantially within and between levels. These differences are partly explained by management quality and partly by the exact combination of technologies used, especially with respect to greenhouse construction, irrigation, and climate control. As a result, a classification based only on technology level would not sufficiently capture the variation relevant for water use.

For that reason, results of the stepping stone analysis were translated into three broader production categories: low-production, medium-production and high-production systems. These categories provide a more functional basis for the remainder of the analysis, because they better reflect the observed variation in production performance while still retaining the broader system characteristics described in the stepping-stone matrix.

With regards to water use, the stepping stones show that higher-producing systems use water for irrigation in a similar way to other systems, but increasingly also use water for climate control. In particular, systems aimed at higher and more stable production may apply cooling techniques such as misting, pad-and-fan cooling and air conditioning. Misting and pad-and-fan systems can improve growing conditions and support higher yields, but require more water. Even where higher-producing systems achieve better water-use efficiency per kilogram of tomatoes when considering irrigation water alone, this does not necessarily translate in less absolute water use per hectare, as additional water is often required for cooling and climate control.

Overall, the stepping-stone analysis provides the conceptual basis for distinguishing production systems in the remainder of this report. While the original nine levels remain useful as a descriptive framework, the comparison of water and energy use in the following sections is based on the distinction between low-, medium-, and high-production systems.

Table 1. The stepping-stone matrix

System	Level	Structure	Irrigation	Climate control	Nutrients	Cultivation method	Disease control	Heating source
High-production system	9	Glass greenhouse	Fully automated drip system with recirculation, disinfection and AI control	Closed greenhouse with air conditioning and water condensation recovery	Liquid individual elements, injection system, automated EC control	Substrate-bound	Integrated pest management	Hot water boiler + CHP + geothermal
	8	Glass greenhouse	Closed drip system with recirculation and disinfection	Climate computer control with pad-and-fan system or high-pressure fogging	Liquid individual elements, A + B tank system, automated EC control	Substrate-bound	Integrated pest management	Hot water boiler + CHP
	7	Glass greenhouse	Drip irrigation with fertigation	Climate computer control with mechanical ventilation	Solid individual elements, A + B tank system, automated EC control	Substrate-bound	Integrated pest management	Hot water boiler
Medium-production system	6	Multi-plastic tunnel	Pressure-compensated drippers with sensors/timers	Mechanical ventilation and pad-and-fan system or high-pressure fogging	Solid individual elements, A + B tank system, manual EC control	Substrate-bound	Integrated pest management	Hot water boiler
	5	Multi-plastic tunnel	Simple drip irrigation (drip tape or spaghetti hose)	Natural ventilation and simple automation	Solid individual elements, A + B tank system, manual EC control	Soil-bound	Chemical control	Hot water boiler
	4	Multi-plastic tunnel	Stationary sprinkler systems (pivot/linear)	Manual ventilation	Premixed solid fertiliser	Soil-bound	Chemical control	Not present
Low-production system	3	Single plastic tunnel	Mobile overhead sprinklers or irrigation booms	Low-tunnel greenhouses	Premixed solid fertiliser	Soil-bound	Chemical control	Not present
	2	Single plastic tunnel	Open-field, superficial irrigation (furrow, border, basin)	Greenhouse shade nets or temporary cover	Additional by hand	Soil-bound	Chemical control	Not present
	1	Open field	Open-field, manual pouring	No climate control	No additional nutrients	Soil-bound	None	Not present

3.2 Water and energy use based on literature

The 15 scientific papers and reports with data on water use led to 35 data points. We derived 10 data points for greenhouses with low productivity (< 10 kg/m^2), 13 for those with medium productivity (10–40 kg/m^2) and 12 for those with high productivity (> 40 kg/m^2).

Data for greenhouses with low productivity were based on monitoring studies from Jordan (Brunsting, 2019), Lebanon (Van Os *et al*., 2019) and Spain (Sanchez *et al*. 2015; Reja *et al*., 2025). Average productivity is 4.8 kg/m^2/year (range from 2 to 9 kg/m^2/year), and generally production was limited to either summer or winter/spring, depending on the most favourable climatic conditions. Most (73%) greenhouses were Canarian greenhouses or multi-span constructions, while 27% consisted of low tunnels. Cultivation was generally in soil (60%). Cooling (Figure 1) was done by natural ventilation, either (70%) manual (stepping stones 2–4) or by a simple automated system (stepping stone 5). Irrigation was done by sprinklers (30%, stepping stones 2 and 3) or by drip irrigation. When drip irrigation was used, it was generally combined with fertigation.

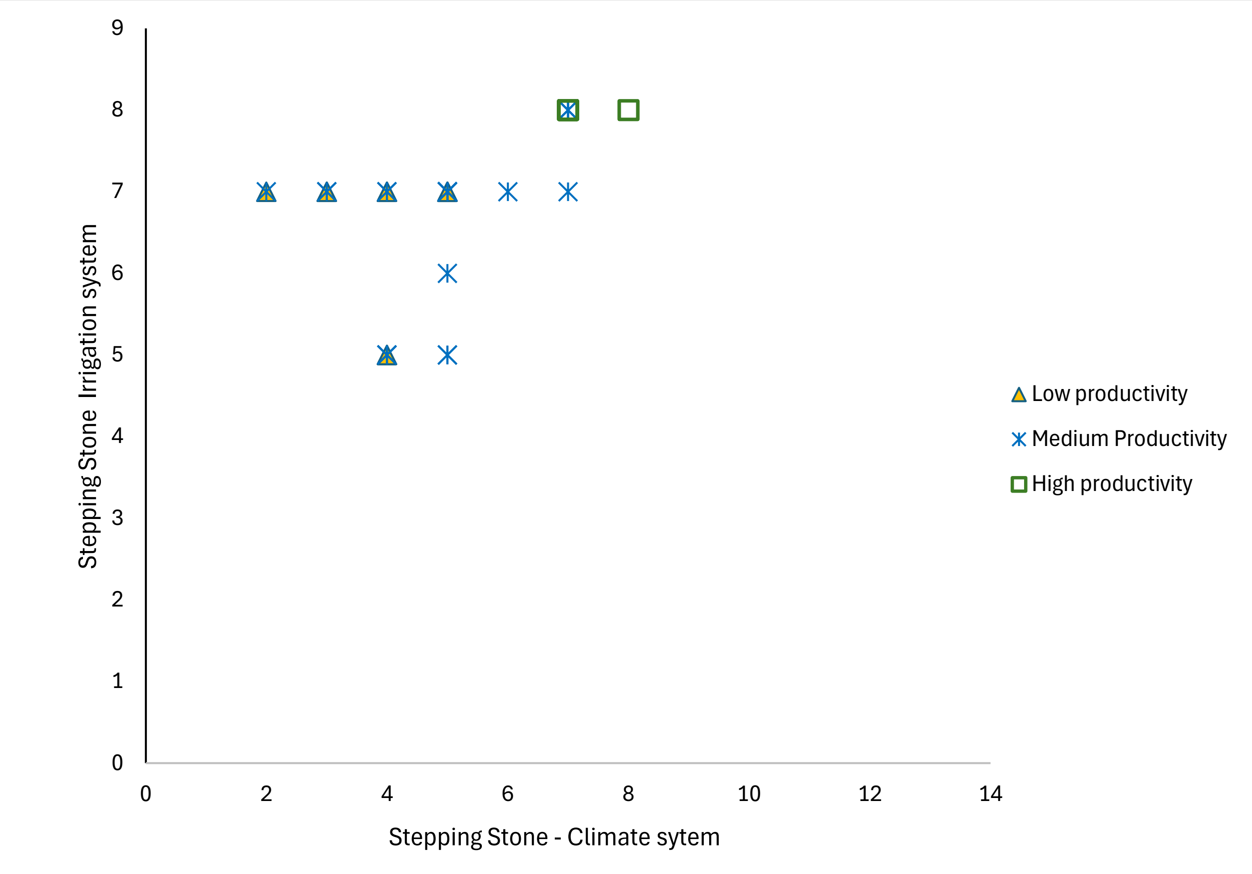

Figure 1. Distribution of the data points over the stepping stones for climate and irrigation

Water use for the low-production greenhouses ranged from 1,957 to 4,070 m^3/ha, with an average of 3,056 m^3/ha and a median of 3,046 m^3/ha. Product water use ranged from 42 to 107 L/kg. No data were found on energy use for this category, but this is most likely very limited, as no energy is used for climate control.

Data for greenhouses with medium productivity were based on monitoring and model studies from the United Arab Emirates (UAE) (Hirich *et al*., 2017), Jordan (Brunsting, 2019), Algeria (Van der Salm *et al*, 2023), Morocco (Payen *et al*., 2015), Turkey (Yilderum and Bahar, 2016), Greece (Katsoulas, 2026) and Italy (Vallenzano *et al*., 2008). Average productivity is 21.2 kg/m^2/year (range from 11 to 39 kg/m^2/year) and generally the production period was longer than for the low-production greenhouses. Most (85%)

greenhouses were multi-span constructions. Cultivation was generally on substrate (80%). Climate systems used were between stepping stones 4 and 7 (Figure 1), and irrigation systems between stepping stones 5 and 8. In hotter climates (UAE, Turkey, Algeria), greenhouses used pad-and-fan cooling systems. In Italy and Jordan, cooling was done by natural ventilation. Irrigation was done by drip irrigation, often combined with fertigation. In 30% of cases, drainage water was recycled.

Water use for the medium-production greenhouses ranged from 5,550 to 14,644 m^3/ha, with an average of 8,396 m^3/ha and a median of 7,935 m^3/ha. Product water use ranged from 22 to 67 L/kg, with an average of 41 L/kg. The high water consumption in some greenhouses is due to the use of water for cooling (pad-and-fan systems). Water use for irrigation only ranged from 5,550 to 10,709 m^3/ha, with an average of 7,701 m^3/ha and a median of 7,935 m^3/ha.

Energy use ranged from 3 to 30 kWh/m^2, with the higher value related to the use of a pad-and-fan system. Data for greenhouses with high productivity were based on monitoring and model studies from Saudi Arabia (Campen *et al*., 2020; Goddek *et al*., 2021; Tsafaras *et al*., 2021 and 2022), Algeria (Van der Salm *et al*., 2023), and Spain (Goddek *et al*., 2021). Average productivity is 72.0 kg/m^2/year (range from 45 to 90 kg/m^2/year), and generally the production period was year-round or almost year-round. Most (85%) greenhouses were multi-span or glasshouse constructions. Cultivation was generally on substrate (80%). Climate and irrigation systems used were between stepping stones 7 and 8 (Figure 1).

The data fall into two categories: (i) with air conditioning (airco); and (ii) with heating or a pad-and-fan system. Water use for greenhouses with airco was very low as condensation water was reused for irrigation. However, annual energy use ranged from 300 to 600 kWh/m^2. Water use for greenhouses without airco ranged from 22,665 to 64,430 m^3/ha, of which on average 65% was used for cooling. Water use for irrigation ranged from 9,800 to 19,990 m^3/ha, with an average of 14,040 m^3/ha. Product water use ranged from 32 to 105 L/kg, with an average of 62 L/kg. Energy use for this category of greenhouse was about 33 kWh/m^2.

When we only consider water use for irrigation, we find a reasonable relationship between yield and total water use, despite variations in technology and management (Figure 2). The figure illustrates that an increase in yield of 1 kg/m^2 leads to an increase in water use for irrigation of 143 m^3/ha (slope of the line). It also illustrates that product water use declines from 31 L/kg at a yield of 20 kg/m^2 to 23 L/kg at a yield of 40 kg/m^2. However, the picture changes dramatically when water is needed for cooling to achieve this increased yield (Figure 3).

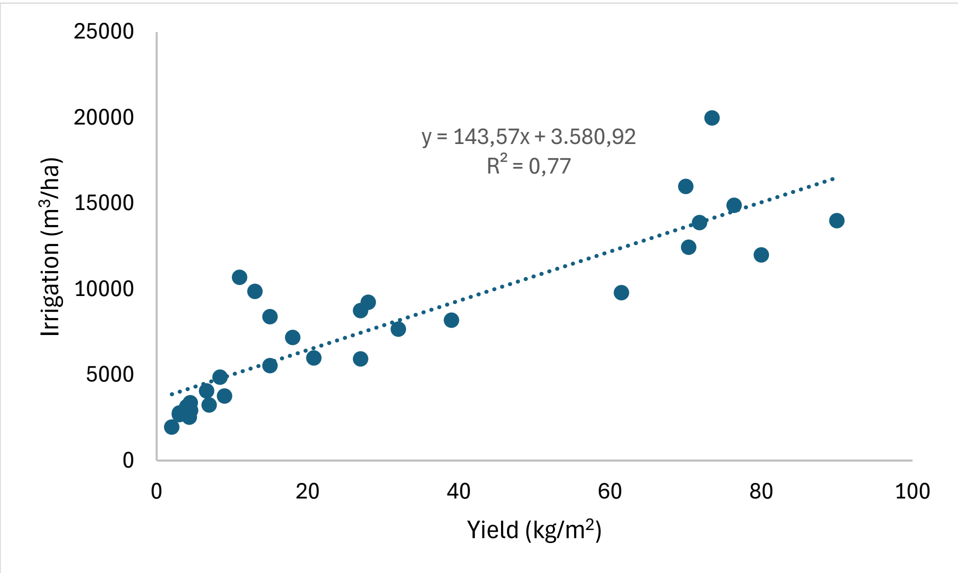

Figure 2. Relationship between irrigation and yield in literature data from North Africa and the Middle East

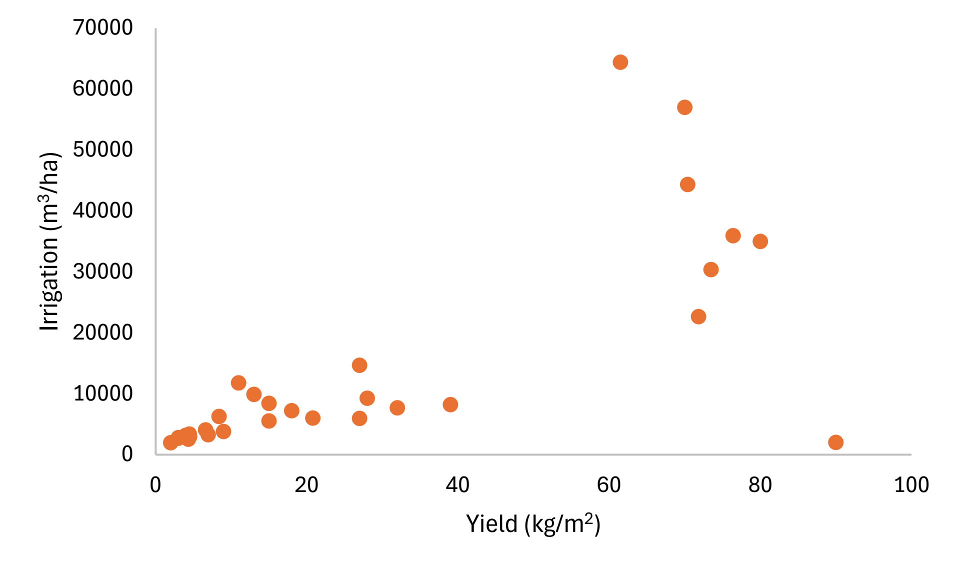

Figure 3. Relationship between total water use (for irrigation and cooling) and yield in literature data from North Africa and the Middle East

Data on energy use were limited to 10 data points, of which seven were related to high-production systems and three to medium-production systems. The lack of data on low-production systems is not surprising as these systems typically have less energy-use equipment. In medium-production systems, energy use was from 3 to 4 KWh/m^2 for the situations without a pad-and-fan system, and 30 KWh/m^2 for the data point with a pad-and-fan system. In high-production systems, the values ranged from 30 to 35 KWh/m^2 for greenhouses with a pad-and-fan system, and from 560 to 600 KWh/m^2 for greenhouses with airco.

3.3 Composition of a horticultural greenhouse cluster

3.3.1 Introduction

This section outlines a baseline scenario for tomato cultivation in the fictitious country of Azuria, representing conditions in North Africa. The scenario functioned as a neutral reference point for the analysis of water consumption within the horticultural sector in North Africa. The analysis was deliberately restricted to tomato production and to two sharply contrasting agro-climatic zones, to elucidate as clearly as possible the interactions between climate, greenhouse technology, and water use.

In the baseline scenario, the desert zone and the coastal zone encompass 1,000 ha of greenhouse tomato cultivation each, resulting in a total cultivated area of 2,000 ha in Azuria. Each zone has an identical distribution of low-, medium-, and high-production systems. This uniform area structure ensures that observed differences in production performance and water consumption can be attributed primarily to climatic conditions and water availability, rather than to structural differences in cultivated area.

A central principle of this baseline scenario is the adoption of a combined irrigation and cooling water perspective on water use. Reported water consumption includes both irrigation water and water used to cool greenhouses. Under hot and arid conditions — characterised by negligible rainfall, evapotranspiration exceeding precipitation, and limited water availability — cooling constitutes a critical component of the production system, rather than a marginal input. Moreover, the cooling and irrigation technologies employed in desert and coastal environments differ fundamentally, reflecting their climatic and hydrological contexts.

3.3.2 Overview of horticultural areas and clusters

Desert zone

The desert zone represents the most extreme production environment within Azuria. The region is located far inland and is characterised by very high summer temperatures, low relative humidity, and intense solar radiation. For large parts of the year, ambient temperatures exceed the physiological tolerance thresholds of tomato plants, rendering cultivation impossible without active climate-control measures.

Greenhouse horticulture in the desert zone therefore operates as a highly controlled productive enclave. Water is sourced almost exclusively from deep groundwater or fossil aquifers that were formed under markedly different climatic conditions in the geological past. Although these water sources remain technically exploitable, they exhibit negligible renewability, which elevates water management to a strategic consideration. The virtual absence of precipitation implies that both irrigation and greenhouse cooling depend entirely on externally extracted water.

The business structure in the desert zone differs substantially from that of the coastal region. In addition to small-scale, low-production farms that produce crops in winter with minimal capital investment, there exists a significant segment of mid-tech enterprises utilising improved greenhouse designs with enhanced ventilation and active cooling systems. The high-production segment occupies a comparatively limited share of the cultivated area but is of considerable economic and technological importance. These operations are frequently established with foreign investment, state support, or agro-industrial partnerships, and rely heavily on imported technologies, specialised inputs, and external expertise.

Water availability and sources in the desert zone

The desert zone is characterised by a fundamentally distinct water context compared to the coastal zone. Whereas coastal systems retain some degree of hydrological dynamism and partial renewability, water availability in the desert is almost entirely dependent on deep groundwater aquifers that receive little to no replenishment under current climatic conditions. Rainfall in the region is sparse and highly irregular, and contributes negligibly to aquifer replenishment.

Most water used for tomato cultivation in the desert zone is abstracted from deep, often fossil groundwater reserves. These aquifers were formed during earlier geological periods under wetter climatic regimes and are effectively non-renewable in the present context. As such, water availability is not governed by inter-annual rainfall variability, but by technical and economic extractability. As long as water can be pumped at an acceptable cost, it appears available in operational terms, even though it is a hydrologically finite resource.

In practice, this leads to a perception among growers and investors that water is 'sufficiently available', given that large volumes can be secured in the short term. However, this apparent availability is inherently fragile. As groundwater levels decline, wells must be drilled deeper, resulting in rising energy requirements and increasing salinity levels. This pattern has been extensively documented in comparable desert regions, including southern Tunisia and the Algerian Sahara, and large-scale desert agriculture projects in Egypt.

Within greenhouse horticulture, water thus functions not merely as an input, but as a strategic prerequisite that strongly shapes technological choices and investment decisions. Low-production systems tend to use relatively limited volumes of water but often lack precise control and exhibit low water efficiency per kilogram of tomato output. Medium- and high-production systems, by contrast, display substantially higher absolute water use per hectare, primarily due to the need for active cooling (pad-and-fan system). As a result, water efficiency per unit of product shows little improvement. This creates a paradox in which the most capital- and technology-intensive systems may represent more efficient use of water per unit of output, despite their very high total water demand driven by cooling requirements.

In contrast to coastal regions, there is little to no experimentation with seawater desalination in desert areas, owing to the substantial distance from the coastline and the prohibitive transport and energy costs involved. Alternative water sources remain limited to the internal re-use of drainage water within high-production systems and to a small number of pilot projects involving advanced water treatment. Within the baseline scenario, these alternatives do not constitute a structural supplement to groundwater abstraction.

The necessary greenhouse cooling in the desert zone is almost exclusively achieved through pad-and-fan systems, which are particularly effective under the low ambient humidity typical of the desert climate; only a small share of the high-production cultivation is equipped with air conditioning as a cooling system. Pad-and-fan systems rely on evaporative cooling and therefore consume substantial volumes of water. From a hydrological perspective, cooling water thus represents the dominant component of total water consumption in medium- and high-tech greenhouses in the desert region. This highlights that water use in this context is driven not only by crop water requirements, but to a large extent by the demands of climate regulation.

Coastal zone

The coastal zone constitutes the temperate horticultural region of Azuria. It is situated along the coastal plain and is characterised by a Mediterranean climate, with relatively mild summers, limited temperature extremes, and substantially higher humidity than in inland areas. These agro-climatic conditions have historically made the region well suited to intensive vegetable production under protected cultivation systems.

The development of horticulture in the coastal zone is closely linked to the availability of logistics infrastructure. The presence of seaports, cold-storage facilities, and efficient transport corridors facilitates relatively rapid distribution to both domestic urban markets and export destinations. As a result, horticultural production in this region places greater emphasis on product quality, supply reliability, and continuity throughout the year, rather than on maximising short-term seasonal peaks.

The business structure within the coastal zone is heterogeneous. A substantial share of the cultivated area is managed by local family-owned enterprises employing simple tunnel structures and largely traditional production practices. Alongside these, a distinct group of medium-sized commercial growers has emerged, characterised by investments in modern multi-span greenhouses with improved climate control capabilities. High-production greenhouse systems are present but remain relatively limited in number and are often associated with collaborations involving foreign investors, technology providers, or input suppliers.
The coastal zone also benefits from a comparatively well-developed knowledge infrastructure, including regional experimental fields, specialised crop advisors, and training centres focused on greenhouse horticulture under Mediterranean conditions.

Water availability and sources in the coastal zone

Water availability in the coastal zone differs fundamentally from that in the desert zone and represents a key determinant of the technological and agronomic choices observed in tomato cultivation. Whereas water resources in the desert zone are primarily technically extractable but hydrologically finite, the coastal zone is characterised by a more dynamic and partly renewable water system, albeit one that is increasingly subject to structural pressure.

The majority of irrigation water used in greenhouse horticulture in the Azurian coastal zone is abstracted from shallow and medium-depth groundwater aquifers, a situation comparable to that found in coastal regions of Morocco and Spain, and parts of southern Italy. These aquifers are partly recharged by precipitation in the hinterland and, to a lesser extent, by surface runoff from adjacent hilly areas.
This hydrological context provides a degree of natural replenishment, rendering water resources comparatively less finite than those in arid desert environments.

In daily practice, growers in the coastal zone generally perceive water as 'available', especially compared to the inland areas. Wells are relatively shallow, energy consumption for pumping remains within acceptable limits, and water salinity is often suitable for tomato cultivation without extensive treatment. This explains why low- and medium-production farms have historically been able to develop without complex water technologies, and why full-field irrigation and simple drip irrigation have remained dominant for a long time.

However, this apparent water security (quantity and quality) is increasingly under threat. Agricultural intensification, urban expansion, and the impacts of climate change are placing growing pressure on coastal groundwater resources in Azuria, mirroring developments observed in other Mediterranean regions. A key risk in this context is saltwater intrusion, whereby excessive groundwater abstraction allows seawater to infiltrate freshwater aquifers, leading to lower water quality. This phenomenon has been extensively documented in coastal plains in Morocco and Spain, and represents a tangible medium-term risk for the Azurian coastal zone.

In response to these pressures, experimental and supplementary water strategies are gradually being introduced. Several high-technology greenhouse projects are exploring the blending of groundwater with water produced by reverse osmosis (RO) desalination plants, thereby rendering brackish or moderately saline water suitable for irrigation. Within the baseline (0) scenario, such applications remain limited to pilot-scale initiatives, as the high costs associated with desalination and energy consumption restrict economic viability to intensive production systems with high yields per square metre.

Consideration is also being given to the potential re-use of treated urban wastewater, particularly for applications that avoid direct contact with the crop and that incorporate additional treatment steps. As in many Mediterranean countries, however, the large-scale adoption of wastewater re-use is constrained by institutional barriers, quality perceptions, and infrastructural limitations. Consequently, in the baseline scenario, wastewater does not constitute a major water source but is acknowledged as a strategic option for future development.

With respect to greenhouse cooling, the prevailing water and climate conditions in the coastal zone play a decisive role in determining the technologies applied. Owing to higher relative humidity and less extreme temperature peaks, fogging systems (mist-based cooling) are generally sufficient as the primary cooling strategy in medium- and high-intensity greenhouses. These systems rely on finely atomised water to moderate peak temperatures and reduce heat stress, without the substantial water volumes associated with pad-and-fan cooling systems. As a result, water consumption for cooling in the coastal zone remains significantly lower than in desert environments, which is directly reflected in the total per-hectare water use reported for the baseline scenario.

3.3.3 Scale, area under cultivation, and production profile

In this baseline '0' scenario, both the coastal zone and the desert zone comprise 1,000 ha of tomato cultivation in greenhouses (See Table 2). The distribution across production systems is identical in both regions. The yields in Table 2 reflect the significant influence of climate control, cultivation systems, and water management on tomato productivity in both areas.

Table 2. Breakdown of area under cultivation by region and tomato yields by production system

Production system	Coastal area tomato ha	Desert area tomato ha	Yield tonnes/ha
Low-production system	600	600	48
Medium-production system	300	300	212
High-production system	100	100	720
	1,000	1,000	

3.3.4 Production system typology (low/medium/high) and applied technology

The production levels on which the differentiation between low-, medium-, and high-production systems is based clearly relate to the greenhouse design applied, the degree of climate control, and water and irrigation technologies, and the combination thereof. In addition, the level of crop and quality management, together with organisational capacities, plays a significant role in achieving specific tomato production levels.

It is emphasised once again that the categorisation into low-, medium-, and high-production systems in this report is not based on the availability or level of applied technologies per se, but rather on production output. Nevertheless, a distinct relationship can be observed between production output and the technologies and technology levels employed. Below are descriptions of technologies predominantly applied within production system of different levels in North Africa.

Low-production systems consist of simple plastic tunnels or arched greenhouses with a single-layer plastic cover and limited structural height. Cultivation is soil based, with no physical separation between the root zone and the underlying soil. Irrigation is generally conducted through full-field methods, such as hoses or rudimentary sprinkler systems, without active monitoring or automated control. Decisions regarding irrigation timing and water volumes are predominantly based on grower experience, fixed schedules, and visual crop assessment. No sensors are used, and there are no facilities to collect or re-use drainage water. While these systems are characterised by minimal investment and operational simplicity, their water-use efficiency is low. They are prone to both over- and under-irrigation, leading to water and nutrient losses as well as variable product quality. Consequently, low-technology tunnels are therefore mainly used in situations where water is temporarily and relatively cheaply available, or where investment capacity is limited.

Medium-production systems are more advanced in structural design and water management. These systems are generally multi-span or Canarian-type greenhouses with greater roof height, ventilation capacity, and structural stability. Irrigation is provided through drip systems, enabling more targeted application of water and nutrients to the root zone. Cultivation may take place in gutters or raised beds, although production often remains at least partially soil-based. Drainage water is typically not fully collected or recirculated. Compared to low-production systems, water management is more precise, yet still relatively limited. Irrigation decisions are frequently made manually or supported by simple timers, with only restricted feedback from crop or substrate conditions. Medium-production systems are therefore more water- and nutrient-efficient, but still experience losses, particularly during periods of high temperatures when both irrigation and cooling demands increase.

High-production systems are the most technologically advanced segment of greenhouse tomato cultivation. These systems consist of fully controlled multi-span greenhouses that employ soil-less cultivation on substrates, such as rockwool or coconut fibre mats, in which the root environment is entirely isolated from the underlying soil. Irrigation is delivered via drip systems combined with full recirculation of drainage water. Excess water is collected, disinfected, and re-used, thereby minimising losses. Irrigation is governed by advanced control systems with integrated sensors that monitor electrical conductivity (EC), pH, substrate moisture content, climatic variables, and, in some cases, crop growth indicators. This allows water and nutrient supply to be closely aligned with the crop’s real-time physiological requirements.

3.3.5 Climate, temperature, and humidity

The coastal region experiences average summer temperatures of approximately 25–30 °C, combined with relative humidity levels of 50–70%, resulting in a greenhouse heat load that remains relatively manageable. By contrast, the desert zone is characterised by summer temperatures reaching 45–48 °C and low relative humidity in the range of 15–30%, conditions that generate extreme heat stress in the absence of active cooling systems.

3.3.6 Water availability, irrigation, and cooling

Within the baseline (‘0’) scenario, water use per hectare is disaggregated into water applied to irrigate crops and water used to cool greenhouses. This distinction is essential for identifying the structural drivers of water consumption, particularly under hot and arid growing conditions where cooling requirements may constitute the dominant component of total water use.

Irrigation water is directly associated with the tomato crop’s water and nutrient demands, and is primarily determined by the cultivation system employed (soil-based versus substrate cultivation), the level of irrigation control, and the extent to which drainage water is collected and re-used. Cooling water, by contrast, is largely determined by the greenhouse climate system and increases principally in response to higher outdoor temperatures, elevated levels of solar radiation, and a greater number of hours during which critical temperature thresholds are exceeded.

3.4 Model calculations based on scenarios

3.4.1 Summary baseline scenario

Based on the theoretical framework for a representative horticultural cluster in North Africa, as elaborated in Section 3.3, a set of scenarios were developed for the model calculations. The baseline scenario is defined as a fictitious horticultural cluster comprising 1,000 ha of greenhouse tomato cultivation in each of two distinct climatic zones in North Africa, namely:

1. Desert zone
   The desert zone represents the extreme production environment of Azuria. The region is located far from the coast and is characterised by very high summer temperatures, low relative humidity, and intense solar radiation. For a large part of the year, ambient temperatures exceed the physiological tolerance limit of tomato plants, rendering production impossible without active climate control.

2. Coastal zone
   The coastal zone constitutes the temperate horticultural region of Azuria. It is situated along the coastal plain and is characterised by a Mediterranean climate, with relatively mild summers, limited temperature extremes, and significantly higher humidity than inland areas. These conditions have historically made the region suitable for intensive vegetable production under protected cultivation.

Within the baseline ('0') scenario, the production area of 1,000 ha in each climatic zone is composed of an identical distribution of production system types: 60% (600 ha) low-production systems, 30% (300 ha) medium-production systems, and 10% (100 ha) high-production systems.

For the purposes of this analysis, the annual production yields of 4.8, 21.2, and 72.0 kg of tomatoes per square metre for low-, medium-, and high-production systems, respectively, are derived from empirical data and literature. The classification and characteristics of these production system levels are further substantiated in Section 3.2.

3.4.2 Water consumption per production system, disaggregated by irrigation and cooling

In the desert zone, two cooling technologies are technically applicable for high-production greenhouse systems: pad-and-fan cooling and air conditioning. The use of an air-conditioning system allows for the near-complete closure of the water cycle within the greenhouse, as cooling water can be fully recirculated. However, the electricity demand associated with air conditioning is extremely high, resulting in substantial operating costs. As a consequence, this technology is economically viable only in a limited number of cases within the business model of tomato cultivation. For the scenario analyses of high-production systems in the desert zone, it is therefore assumed that the cultivated area with high-production systems is divided between greenhouses equipped with pad-and-fan systems (90%) and those using air conditioning (10%).

In the coastal climate zone, greenhouse cooling requirements for high-production systems can be met through fogging (mist-based cooling). Compared with active evaporative cooling via pad-and-fan systems, fogging uses substantially less water to regulate the climate.

In both climatic zones, transitioning towards higher production system levels results in higher total water consumption for irrigation and cooling at the cluster level, with total water use for the high-production systems in the desert zone being particularly notable at 40,746 litres per hectare per year. The combined water use for irrigation and cooling per unit of product only decreases significantly in the transition from medium-production systems to high-production systems in the coastal area, where fogging is assumed to be used for cooling. Further technological intensification of the production area does not, despite the associated improvements in water-use efficiency, necessarily result in lower total water consumption within horticultural clusters in the coastal region. A decline in overall water use can only occur if technological upgrades are accompanied by a contraction of the total cultivated area, enabled by higher production yields per square metre (kg/m^2/year). Where technological intensification takes place while the cultivated area remains constant or expands, total combined water use for irrigation and cooling will increase, notwithstanding the higher efficiency of water use per unit of output.

Table 3 illustrates that in the desert zone, water use for greenhouse cooling is a decisive component of total water consumption, particularly in high-production systems. Low-production systems typically operate without active cooling and are therefore restricted to seasons during which ambient temperatures remain marginally within cultivable limits. Once higher productivity levels and year-round cultivation are pursued, the implementation of active cooling becomes unavoidable.

In the present scenario, active cooling in the desert zone is achieved through pad-and-fan systems, which rely exclusively on evaporative cooling and consequently require substantial volumes of water. In high-production systems, water consumption for cooling even exceeds irrigation water demand. This explicitly underscores that, under arid conditions, water use is driven primarily by climate regulation requirements and only secondarily by crop water needs. This results in total water use in high-production systems being 13 times higher than in low-production systems. If only irrigation water is taken into account, high-production systems use more than four times more water compared to low-production systems.

Table 3. Water consumption in the desert zone (excluding high-production systems with air conditioning)

Production system	Irrigation L/ha/year	Cooling L/ha/year	Total L/ha/year	Total L/kg yield
Low-production system	3,056	0	3,056	63.7
Medium-production system	7,701	758	8,459	39.9
High-production system	14,040	26,706	40,746	56.6

In high-production systems in the coastal zone, the contribution of cooling water to total water consumption (39%) is also substantial, but significantly lower than the contribution of cooling water to total water consumption in high-production systems equipped with pad-and-fan systems in the desert zone (66%).
The more moderate temperature regime and higher relative humidity in the coastal zone permit greenhouse cooling to be achieved primarily through fogging (mist-based systems), which require less water to attenuate peak temperatures and mitigate heat stress (see Table 4). In this context, cooling serves mainly as a supporting mechanism rather than as a primary precondition for production, as is the case in the desert zone.

Table 4. Water consumption in the coastal zone

Production system	Irrigation L/ha/year	Cooling L/ha/year	Total L/ha/year	Total L/kg yield
Low-production system	3,056	0	3,056	63.7
Medium-production system	7,701	300	8,001	37.8
High-production system	14,040	9,000	23,040	32.0

Irrigation water therefore constitutes the dominant component of total water consumption in the coastal region, particularly within low- and medium-production systems. In high-production greenhouses, absolute water use increases as a result of higher yields and greater production intensity; however, the proportional contribution of cooling water is less when compared with desert zone scenarios. Also, in the coastal area, total water consumption is much higher for high-production systems than for low-production systems, about seven and a half times higher.

In Table 5, the production volumes and water use of a company with a cultivation area of 10 ha in each of the two climate zones, and production systems of various levels, are shown.

Table 5. Analysis of water use at the company level (with a cultivation area of 10 ha)

Production system	Cultivation area ha	Average yield kg/m²	Total yield 1,000 kg	Water use – irrigation m³/ha	Water use – cooling m³/ha	Water use – combined m³/ha	Energy use MWh/ha	Total water use m³	Total energy use MWh	Total water use L/kg	Total energy use kWh/kg
Desert zone tomato cultivation											
Low-production	10	4.8	480	3,056	—	3,056	30	30,560	300	63.7	0.6
Medium-production	10	21.2	2,118	7,701	758	8,459	120	84,590	1,200	39.9	0.6
High-production, pad-and-fan	10	72.0	7,200	14,040	26,706	40,746	330	407,460	3,300	56.6	0.5
High-production, airco	10	72.0	7,200	14,000	12,000	2,000	5,800	20,000	58,000	2.8	8.1
Coastal zone tomato cultivation											
Low-production	10	4.8	480	3,056	—	3,056	30	30,560	300	63.7	0.6
Medium-production	10	21.2	2,118	7,701	300	8,001	120	80,010	1,200	37.8	0.6
High-production, fogging	10	72.0	7,200	14,040	9,000	23,040	200	230,400	2,000	32.0	0.3

3.4.3 Scenario calculations

To assess the effects of shifts in the distribution of production system levels on both absolute and relative water use, several additional scenarios were defined. These scenarios build upon the baseline configuration and explore alternative development pathways for the horticultural cluster.

Scenario 1 represents a modification of the baseline scenario in which the distribution of production system levels (low–medium–high) changes to 40%, 45%, and 15%, respectively, while the total cultivated area of the cluster remains constant. This scenario assumes that a portion of the existing production area is upgraded to higher production system levels, resulting in greater total production output for the cluster.

Scenario 2 also involves a redistribution of production system levels to 40%, 45%, and 15%, respectively, identical in proportional terms to Scenario 1, but is defined under the condition that total cluster production output remains constant. In this case, the shift towards higher production systems is accompanied by a contraction of the total cultivated area, such that the aggregate tomato yield of the cluster does not change.

Scenario 3 combines the same redistribution of production system levels (40%, 45%, and 15%, respectively) with expansion of the total cultivated area by 10%. This scenario assumes that the transition towards more advanced production systems generates a reinforcing effect, stimulating further expansion of the overall production area.

The following sections present a detailed analysis of production volumes and water use for both climatic zones across all four scenarios — comprising the baseline scenario and the three development scenarios — disaggregated by climatic zone (Table 6 and Table 7).

In Table 6 (desert zone), the baseline scenario shows that the efficiency of water use (total water use in L/kg) decreases as further technological intensification occurs; 63.7, 39.9 and 56.6 L/kg for low-, medium-, and high-production, respectively. The reason this decrease is limited in the high-production system is the increased water use for pad-and-fan systems. Table 6 indicates that, under desert climatic conditions (desert zone), technological intensification of the production area while maintaining a constant total cultivated area (Scenario 1) results in a substantial increase in total production output, from 164,340 tonnes to 222,510 tonnes per year (+35%). At the same time, water-use efficiency remains more or less the same, with water efficiency declining slightly from 49.0 L/kg to 48.3 L/kg (-1.4%). Nevertheless, total water consumption for the 1,000 ha cluster increases markedly, rising from approximately 8.1 million m^3/year to 10.7 million m^3/year (+33.4%).

When total production output is held constant and the cultivated area is proportionally reduced (-26%) and redistributed between low-, medium-, and high-production systems (Scenario 2), virtually no improvements are observed, either in relative or absolute terms. This outcome is attributable to a substantial increase in water consumption associated with pad-and-fan systems, which consequently drives up total water use per hectare but doesn’t result in less relative water use expressed in litres per kilogram of yield.

In Scenario 3, where the total cultivated area expands, both total production output and total water consumption increase further, reflecting the combined effects of area growth and higher production intensity. In the coastal zone, total water consumption increases by 39%, from 6.5 million m^3 to 9.1 million m^3, and in the desert zone by 47%, from 8.1 million m^3 to 11.8 million m^3.

In Table 7 (coastal zone), the baseline scenario shows that the efficiency of water use (total water use in L/kg) increases strongly as further technological intensification occurs: 63.7, 37.8 and 32.0 L/kg for low-, medium-, and high-production systems, respectively. The use of fogging systems leads to higher production, while the associated increase in water use is considerable but relatively limited compared to the desert zone.

Table 7 presents analogous results for coastal climatic conditions. Here, further technological intensification under a constant total cultivated area (Scenario 1) also leads to an increase in total production, from 164,340 tonnes to 222,510 tonnes per year (+35%) and improved water-use efficiency, from 39.8 L/kg to

37.2 L/kg (−6.5%). However, total water consumption for the 1,000 ha cluster rises from 6.5 million m^3/year to approximately 8.3 million m^3/year (+27%).
In contrast to the desert zone, maintaining constant production while reducing cultivated area (-26%) (Scenario 2) results in improvements in both relative water use (−6.5%) and absolute water consumption (-6.5%) in the coastal zone. Conversely, expansion of the total production area (Scenario 3) leads to further increases in both total production output and total water use, by 80,420 tonnes and 2.6 million m^3 respectively, compared to the baseline (0).

In summary, according to model calculations further technological intensification of the production area — through a shift towards higher production system levels — combined with a maintained or expanded cultivated area results in a substantial increase in absolute water consumption at the scale of horticultural clusters. This trend can be mitigated under specific conditions, such as the application of desalination systems for seawater use or air-conditioning cooling systems that allow near-complete recirculation of cooling water. However, the amount of energy consumed by these technologies is very high.

Table 6. Overview of scenarios 0 to 3 — desert zone

Desert zone tomato cultivation scenario 0 (baseline)

Production system	Cultivation area ha	Cultivation area distribution	Average yield kg/m²	Total yield ‘1,000 kg	Water use – irrigation m³/ha	Water use – cooling m³/ha	Total water use m³/ha	Energy use MWh/ha	Total water use – irrigation m³	Total water use – cooling m³	Total water use m³	Total energy use MWh	Water use — irrigation L/kg	Water use — cooling L/kg	Total water use L/kg	Total energy use kWh/kg
Low-production	600	60%	4.8	28,800	3,056	–	3,056	30	1,833,600	–	1,833,600	18,000	63.7	–	63.7	0.6
Medium-production	300	30%	21.2	63,540	7,701	758	8,459	120	2,310,300	227,400	2,537,700	36,000	36.4	3.6	39.9	0.6
High-production, pad-and-fan	90	9%	72.0	64,800	14,040	26,706	40,746	330	1,263,600	2,403,540	3,667,140	29,700	19.5	37.1	56.6	0.5
High-production, airco	10	1%	72.0	7,200	14,000	−12,000	2,000	5,800	140,000	−120,000	20,000	58,000	19.4	−16.7	2.8	8.1
	1,000	100%		164,340					5,547,500	2,510,940	8,058,440	141,700			49.0	0.9

Desert zone tomato cultivation scenario 1 (upgrade to higher production system levels, same total cultivation area)

Production system	Cultivation area ha	Cultivation area distribution	Average yield kg/m²	Total yield ‘1,000 kg	Water use – irrigation m³/ha	Water use – cooling m³/ha	Total water use m³/ha	Energy use MWh/ha	Total water use – irrigation m³	Total water use – cooling m³	Total water use m³	Total energy use MWh	Water use — irrigation L/kg	Water use — cooling L/kg	Total water use L/kg	Total energy use kWh/kg
Low-production	400	40%	4.8	19,200	3,056	–	3,056	30	1,222,400	–	1,222,400	12,000	63.7	–	63.7	0.6
Medium-production	450	45%	21.2	95,310	7,701	758	8,459	120	3,465,450	341,100	3,806,550	54,000	36.4	3.6	39.9	0.6
High-production, pad-and-fan	140	14%	72.0	100,800	14,040	26,706	40,746	330	1,965,600	3,738,840	5,704,440	46,200	19.5	37.1	56.6	0.5
High-production, airco	10	1%	72.0	7,200	14,000	−12,000	2,000	5,800	140,000	−120,000	20,000	58,000	19.4	−16.7	2.8	8.1
	1,000	100%		222,510					6,793,450	3,959,940	10,753,390	170,200			48.3	0.8

Desert zone tomato cultivation scenario 2 (upgrade to higher production system levels, same total tomato yield)

Production system	Cultivation area ha	Cultivation area distribution	Average yield kg/m²	Total yield ‘1,000 kg	Water use – irrigation m³/ha	Water use – cooling m³/ha	Total water use m³/ha	Energy use MWh/ha	Total water use – irrigation m³	Total water use – cooling m³	Total water use m³	Total energy use MWh	Water use — irrigation L/kg	Water use — cooling L/kg	Total water use L/kg	Total energy use kWh/kg
Low-production	295	40%	4.8	14,181	3,056	–	3,056	30	902,832	–	902,832	8,863	63.7	–	63.7	0.6
Medium-production	332	45%	21.2	70,393	7,701	758	8,459	120	2,559,490	251,927	2,811,417	39,883	36.4	3.6	39.9	0.6
High-production, pad-and-fan	103	14%	72.0	74,448	14,040	26,706	40,746	330	1,451,740	2,761,408	4,213,148	34,122	19.5	37.1	56.6	0.5
High-production, airco	7	1%	72.0	5,318	14,000	−12,000	2,000	5,800	103,400	−88,629	14,771	42,837	19.4	−16.7	2.8	8.1
	739	100%		164,340					5,017,462	2,924,707	7,942,169	125,705			48.3	0.8

Desert zone tomato cultivation scenario 3 (upgrade to higher production system levels, increase total cultivation area)

Production system	Cultivation area ha	Cultivation area distribution	Average yield kg/m²	Total yield ‘1,000 kg	Water use – irrigation m³/ha	Water use – cooling m³/ha	Total water use m³/ha	Energy use MWh/ha	Total water use – irrigation m³	Total water use – cooling m³	Total water use m³	Total energy use MWh	Water use — irrigation L/kg	Water use — cooling L/kg	Total water use L/kg	Total energy use kWh/kg
Low-production	440	40%	4.8	21,120	3,056	–	3,056	30	1,344,640	–	1,344,640	13,200	63.7	–	63.7	0.6
Medium-production	495	45%	21.2	104,841	7,701	758	8,459	120	3,811,995	375,210	4,187,205	59,400	36.4	3.6	39.9	0.6
High-production, pad-and-fan	154	14%	72.0	110,880	14,040	26,706	40,746	330	2,162,160	4,112,724	6,274,884	50,820	19.5	37.1	56.6	0.5
High-production, airco	11	1%	72.0	7,920	14,000	−12,000	2,000	5,800	154,000	−132,000	22,000	63,800	19.4	−16.7	2.8	8.1
	1,100	100%		244,761					7,472,795	4,355,934	11,828,729	187,220			48.3	0.8

Table 7. Overview of scenarios 0 to 3 — coastal zone

Coastal zone tomato cultivation scenario 0 (baseline)

Production system	Cultivation area ha	Cultivation area distribution	Average yield kg/m^2	Total yield ‘1,000 kg	Water use – irrigation m^3/ha	Water use – cooling m^3/ha	Total water use m^3/ha	Energy use MWh/ha	Total water use – irrigation m^3	Total water use – cooling m^3	Total water use m^3	Total energy use MWh	Water use — irrigation L/kg	Water use — cooling L/kg	Total water use L/kg	Total energy use kWh/kg
Low-production	600	60%	4.8	28,800	3,056	–	3,056	30	1,833,600	–	1,833,600	18,000	63.7	–	63.7	0.6
Medium-production	300	30%	21.2	63,540	7,701	300	8,001	120	2,310,300	90,000	2,400,300	36,000	36.4	1.4	37.8	0.6
High-production, fogging	100	10%	72.0	72,000	14,040	9,000	23,040	200	1,404,000	900,000	2,304,000	20,000	19.5	12.5	32.0	0.3
	1,000	100%		164,340					5,547,900	990,000	6,537,900	74,000			39.8	0.5

Coastal zone tomato cultivation scenario 1 (upgrade to higher production system levels, same total cultivation area)

Production system	Cultivation area ha	Cultivation area distribution	Average yield kg/m^2	Total yield ‘1,000 kg	Water use – irrigation m^3/ha	Water use – cooling m^3/ha	Total water use m^3/ha	Energy use MWh/ha	Total water use – irrigation m^3	Total water use – cooling m^3	Total water use m^3	Total energy use MWh	Water use — irrigation L/kg	Water use — cooling L/kg	Total water use L/kg	Total energy use kWh/kg
Low-production	400	40%	4.8	19,200	3,056	–	3,056	30	1,222,400	–	1,222,400	12,000	63.7	–	63.7	0.6
Medium-production	450	45%	21.2	95,310	7,701	300	8,001	120	3,465,450	135,000	3,600,450	54,000	36.4	1.4	37.8	0.6
High-production, fogging	150	15%	72.0	108,000	14,040	9,000	23,040	200	2,106,000	1,350,000	3,456,000	30,000	19.5	12.5	32.0	0.3
	1,000	100%		222,510					6,793,850	1,485,000	8,278,850	96,000			37.2	0.4

Coastal zone tomato cultivation scenario 2 (upgrade to higher production system levels, same total tomato yield)

Production system	Cultivation area ha	Cultivation area distribution	Average yield kg/m^2	Total yield ‘1,000 kg	Water use – irrigation m^3/ha	Water use – cooling m^3/ha	Total water use m^3/ha	Energy use MWh/ha	Total water use – irrigation m^3	Total water use – cooling m^3	Total water use m^3	Total energy use MWh	Water use — irrigation L/kg	Water use — cooling L/kg	Total water use L/kg	Total energy use kWh/kg
Low-production	295	40%	4.8	14,181	3,056	–	3,056	30	902,832	–	902,832	8,863	63.7	–	63.7	0.6
Medium-production	332	45%	21.2	70,393	7,701	300	8,001	120	2,559,490	99,707	2,659,197	39,883	36.4	1.4	37.8	0.6
High-production, fogging	111	15%	72.0	79,766	14,040	9,000	23,040	200	1,555,436	997,074	2,552,510	22,157	19.5	12.5	32.0	0.3
	739	100%		164,340					5,017,758	1,096,782	6,114,540	70,903			37.2	0.4

Coastal zone tomato cultivation scenario 3 (upgrade to higher production system levels, increase total cultivation area)

Production system	Cultivation area ha	Cultivation area distribution	Average yield kg/m^2	Total yield ‘1,000 kg	Water use – irrigation m^3/ha	Water use – cooling m^3/ha	Total water use m^3/ha	Energy use MWh/ha	Total water use – irrigation m^3	Total water use – cooling m^3	Total water use m^3	Total energy use MWh	Water use — irrigation L/kg	Water use — cooling L/kg	Total water use L/kg	Total energy use kWh/kg
Low-production	440	40%	4.8	21,120	3,056	–	3,056	30	1,344,640	–	1,344,640	13,200	63.7	–	63.7	0.6
Medium-production	495	45%	21.2	104,841	7,701	300	8,001	120	3,811,995	148,500	3,960,495	59,400	36.4	1.4	37.8	0.6
High-production, fogging	165	15%	72.0	118,800	14,040	9,000	23,040	200	2,316,600	1,485,000	3,801,600	33,000	19.5	12.5	32.0	0.3
	1,100	100%		244,761					7,473,235	1,633,500	9,106,735	105,600			37.2	0.4

4 Discussion and conclusions

4.1 Discussion

Jevons paradox

The observation that technological advancement can improve the efficiency with which a natural resource is used, without necessarily reducing consumption of that resource, is well established in the literature and is commonly referred to as the 'Jevons paradox' or 'Jevons effect' (Sears *et al*., 2018; Paul *et al*., 2019).

In economics, the Jevons paradox describes the counter-intuitive phenomenon whereby technological improvements that enhance the efficiency of resource use lead to an increase, rather than a decrease, in total resource consumption. As efficiency improvements reduce the amount of a resource required per unit of application, they effectively lower the resource's marginal cost. Where demand for the associated output is sufficiently price-elastic, this reduction in effective cost can stimulate additional demand, frequently resulting in a net increase in aggregate resource use rather than an absolute reduction (see, for example, Sears *et al*., 2018; Paul *et al*., 2019).

The concept originates from the work of the English economist William Stanley Jevons, who in 1865 observed that technological advances improving the efficiency of coal use led to greater, rather than less, coal consumption across multiple sectors of the British economy. Jevons argued that, contrary to prevailing intuition, technological progress could not be assumed to reduce total fuel use, as efficiency gains often stimulated economic expansion and new applications of the resource.

In contemporary literature, this phenomenon is frequently discussed in terms of rebound effects. Rebound effects, which are particularly complex in the context of agriculture and land-use systems, are where multiple resources — such as land, water, energy, fertilisers, pesticides, and labour — are used simultaneously and interact in non-linear ways. Efficiency gains in one input may therefore lead to indirect increases in the use of other inputs, or enable expansion of production.

Particularly in the field of irrigation, a growing number of studies report outcomes consistent with the Jevons paradox. In their comprehensive literature review, Paul *et al*. (2019) describe this phenomenon as follows:
"More efficient irrigation systems reduce the share of water that is wasted but may also increase the amount of water that is available to plants, resulting in higher consumption. This can result in a hydrological paradox, where water use declines due to higher efficiencies, but water consumption increases, exacerbating water shortages (Gomez and Perez-Blanco, 2014; Grafton et al., 2018).

"Additionally, rebound effects appear to be common, with several studies reporting cases in which rebound effects were greater than 100%, and efficiency improvements resulted in higher, instead of lower, water consumption (Jevons paradox) (e.g. Perry et al., 2017; Pfeiffer and Lin, 2014; Sun et al., 2016). More efficient irrigation systems are likely to induce direct rebound effects because increased water productivity constitutes an economic incentive for farmers to expand their area of irrigated land and to substitute non-irrigated crops for irrigated crops, which result in higher revenues (Kuil et al., 2018; Sears et al., 2018; Wu et al., 2018)."

Evidence from the studies mentioned above conducted in China, the United States, and Australia indicates that government policies aimed at promoting water-saving irrigation technologies to reduce water use have, in several cases, had the opposite effect. Rather than leading to absolute reductions in water consumption, these policy interventions have coincided with increases in total water use.

The underlying mechanism is that technological innovation reduces the marginal cost of water use per unit of production. As water becomes effectively cheaper, it becomes economically attractive for producers to expand water use in ways that enhance financial returns. This may take the form of irrigating a larger area, increasing irrigation intensity per unit of land, or shifting towards higher-value crops that are more water-intensive. Although these responses improve profitability at the farm level, they can collectively lead to higher overall water consumption at regional or sectoral scales.

The adoption of water-saving technologies in a given region depends on a complex interplay of multiple factors. Farm-level economic considerations, including the price and availability of high-quality source water, and the level of entrepreneurship and technical expertise, play a significant role. In addition, the regulatory framework is an important determinant, particularly legislation governing water use and emissions associated with drainage or recirculated water.

In this context, Sears et al. (2018) formulated a number of recommendations for policymakers: *"When designing policies for sustainably managing agricultural groundwater use, policymakers therefore need to account for all the possible behavioural responses to their policy, including any potential unintended perverse consequences that may arise. To do so, it is important for policymakers to continually gather detailed data on the groundwater extraction, groundwater levels, crop acreage, and irrigation technology decisions of individual groundwater users on an ongoing basis, so that researchers can then empirically analyse the effects of past and ongoing policies, and better design future policies.*

"In order to mitigate any potential unintended or perverse consequences, policymakers may wish to consider one or more of the following alternative or complementary aspects of sustainable agricultural groundwater management when designing policy. First, policymakers should consider incorporating insights from behavioural economics, such as behavioural 'nudges' or non-financial changes in the manner in which options are presented to decision makers that may increase the likelihood of a certain behaviour. Second, policy makers should consider reporting the groundwater extraction data they collect to enable groundwater users to make peer comparisons, which has been shown to promote conservation in domestic water use. In addition, the reporting of decisions of non-neighbours may make groundwater users more likely to coordinate with their neighbours.

"Thus, improved monitoring of groundwater extraction and transparent publication of basin-wide information regarding extraction may be important lower-cost alternatives or complements to policies that encourage the adoption of more efficient irrigation technology."

Methodological considerations in interpreting irrigation water-use data

This study draws on average figures for water use derived from 25 empirical studies conducted in North Africa and the Middle East. The compiled data indicate a reasonably strong relationship between production levels and irrigation water use, despite substantial variation in management practices and technological configurations across the studies (Figure 2). This finding is somewhat unexpected, given that irrigation system design and management are known to have a significant influence on water-use efficiency.

For a given level of production, irrigation water use can be substantially reduced through the adoption of technologies such as drip irrigation and the re-use of drainage water via recirculation. However, across most of the reviewed studies, production increases coincided with the introduction of more advanced irrigation technologies. As a result, the water-use efficiency gains achieved through upgrading technology are largely masked by concurrent increases in production intensity, rendering their isolated effect difficult to detect.

It should further be noted that a considerable share of the data used in this study originates from scientific research trials, in which management practices are typically optimised and irrigation systems may themselves constitute an object of experimentation. Consequently, reported water-use figures are likely to reflect best-practice or near-optimal conditions. Actual water consumption in commercial practice may therefore be higher than suggested by the values reported in these studies.

Finally, in the model simulations, average values were applied for the low-, medium-, and high-production categories. It is important to note that the underlying data exhibit considerable variability. This variation indicates that certain producers are able to achieve high yields (kg/m^2) while maintaining relatively low water use. Such cases may serve as exemplars for broader practice within the sector.

Limitations of the classification and baseline assumptions

The classification of low-, medium-, and high-production systems used in this study is, by necessity, partly arbitrary. The distinction between production system levels is based primarily on observed patterns of productivity and water use, rather than on specific physical greenhouse typologies. As a result, the term 'technology level' should be interpreted with caution. A higher production category does not necessarily mean that all technological components of the system are more advanced. Instead, it indicates that the overall combination of infrastructure, management, and resource use results in a greater amount of production. The categories are therefore used in this report as functional production groups, not as strict technical greenhouse types.

The provenance of the water resource is critically important, as the environmental and hydrological implications differ substantially depending on whether water is abstracted from groundwater, surface water, or harvested rainfall, or produced by desalinating seawater. In this study, groundwater was selected as the primary water source, with or without subsequent desalination, depending on local water quality conditions.

The baseline ('0') scenario assumes the technical availability of groundwater resources, particularly in the desert zone, while the long-term sustainability of these groundwater reserves remains uncertain. The scenario does not explicitly account for potential future constraints related to groundwater depletion, declining water quality, or regulatory intervention.

In the baseline ('0') scenario, the share of high-production enterprises within the 1,000 ha tomato cluster is set at 10%, corresponding to 100 ha. These high-production systems are predominantly operated by Dutch companies or by enterprises with foreign investment participation. While this proportion may be relatively high when considered across the entirety of North Africa, it reflects substantial variation between countries and regions. Moreover, continued expansion of this segment has been observed, driven by ongoing investments by Dutch firms and other international investors.

Production from these high-technology enterprises is largely oriented towards export markets, primarily in Europe. This export market continues to expand and increasingly also benefits local enterprises integrated into international supply chains. The present analysis deliberately abstracts from potential risks that could affect these export-oriented production systems, such as geopolitical developments, local or regional water scarcity, or food security concerns. These factors are excluded to maintain a stable analytical framework focused specifically on water-use dynamics within the production system. Furthermore, potential risks to local food security associated with increasing export volumes, as well as prospective water scarcity, are not taken into account.

Finally, the baseline ('0') scenario deliberately excludes external drivers such as climate change, energy prices, and regulatory developments, again to establish a stable and comparable analytical reference. While this approach allows the isolated effects on water use to be examined, it does not capture broader economic, environmental, or institutional impacts that may be relevant under real-world conditions.

Influence of irrigation recirculation and cooling systems

The impacts of technological investments in greenhouse horticulture in North Africa are strongly conditioned by the climatic context, in particular by the necessity and intensity of greenhouse cooling. Even within coastal regions classified as Mediterranean or semi-arid, substantial climatic variation exists. For example, the climate characterising the coastal zone in the baseline scenario — comparable to that of the Agadir region in Morocco — is generally cooler and more humid than that of the eastern Mediterranean coastal zone, exemplified by areas around Algiers. Such climatic differences have significant implications for greenhouse design choices, cooling requirements, and, consequently, overall water consumption.

Empirical experience from Dutch horticultural operators in the Agadir region suggests that the use of pad-and-fan cooling systems is often not required in coastal locations there, and that greenhouse cooling can be adequately achieved using fogging systems alone (personal communication). The combination of moderate temperature extremes and relatively higher humidity reduces the need for intensive evaporative cooling, thereby limiting cooling-related water use.

By contrast, model simulations for the coastal region around Algiers (Van der Salm *et al*., 2023) indicate that pad-and-fan cooling becomes necessary if tomato cultivation continues during summer. Under these conditions, outdoor temperatures exceed critical thresholds for crop performance, making more intensive cooling indispensable. In the same modelling study, winter production — combined with the use of heating — was identified as a more attractive cultivation strategy from both a production and a water-use perspective, as it substantially reduces the need for cooling and results in significantly lower overall water consumption.

These contrasting examples illustrate that actual water use in greenhouse systems is highly sensitive to strategic choices regarding the production season, cooling technology, and precise geographic location. As a consequence, assessments of water consumption and water-use efficiency cannot be generalised solely on the basis of technology level or climate zone classification. Instead, they must explicitly account for the interaction between local climate conditions, production calendars, and the selected combination of irrigation and cooling technologies.

Hydrological systems: water sources and long-term dynamics
Desert groundwater (often comprising fossil water with extremely limited repletion) is treated as 'available' in this study without explicit recognition of its non-renewable nature, therewith ignoring generational responsibility/justice issues. The risks of disturbing hydrological systems, such as depletion and salinisation, are mentioned but not quantified. Although there are studies on these topics, due to limited resources, the long-term system impacts of water use were not considered in this study.

4.2 Conclusions

4.2.1 Overall conclusions

Increased tomato production per square metre in greenhouses in North Africa through further technological intensification leads to greater absolute water consumption
Further technological intensification towards higher-production systems generally leads to greater efficiency. For water use, this efficiency is most evident in the transition to high-production systems in the coastal zone, where fogging is applied for cooling. Although fogging increases absolute water use, this is offset by a proportionally larger increase in tomato production of 48, 212 and 720 tonnes per hectare for low-, medium-, and high-production systems, respectively. Absolute water use amounts to 3,056, 8,001, and 23,040 m^3 per hectare. Consequently, water-use efficiency improves markedly to 63.7, 37.8 and 32.0 litres per kilogram of yield, respectively.

Water-use efficiency barely improves in the desert zone when production system levels increase and pad-and-fan systems are applied
In the desert zone, cooling in high-production systems relies primarily on pad-and-fan systems, which consume substantial volumes of water. Absolute water use rises sharply to 3,056, 8,459, and 40,746 m^3 per hectare for low-, medium-, and high-production systems (excluding air conditioning). Although production levels are comparable to those in the coastal zone, water-use efficiency improves for medium production, however only marginally for high production, with values of 63.7, 39.9 and 56.6 litres per kilogram of yield.

Air conditioning is an extremely water-efficient cooling instrument, but is economically and energetically challenging
An exception within the desert zone is the application of air conditioning. Here, water-use efficiency is extremely high (2.8 litres per kilogram of yield), owing to near-complete recirculation of irrigation water. However, this option requires highly advanced greenhouse technology and substantial capital investment, limiting economic feasibility to exceptional cases. Moreover, energy use is extremely high.

Absolute water use increases substantially when production systems and technology develop to higher levels
Shifting towards higher production system levels substantially increases absolute water use in both zones. Water use per hectare is more than 13 times higher in high-production systems in the desert zone, and seven and a half times higher in the coastal zone, than in low-production systems.

Developing towards higher-production systems leads to a large increase in total water use
With a constant cultivated area and transitioning towards higher production system levels, yield increases by 35%, accompanied by a rise in total water use of 27% in the coastal zone and 33% in the desert zone.

Developing towards higher-production systems leads to substantial land sparing when the **cluster's tomato output remains constant**

A higher-production system increases output per unit area. If total production remains constant, the required greenhouse area can be reduced by up to 26% in both desert and coastal zones. This scenario, however, requires sound land and water governance, and an effective regulatory framework.

Increasing the size of the production area combined with shifting towards higher-production systems leads to a particularly large increase in absolute water use

When the distribution of production system levels shifts and total greenhouse area increases by 10%, absolute water use rises substantially: by 39% in the coastal zone and 47% in the desert zone. Given current estimates of greenhouse expansion rates in North Africa, this scenario appears the most probable. However, additional efforts will be required to facilitate a transition towards more strategically planned horticultural development that prioritises land-sparing approaches.

Energy use is an important trade-off when selecting cooling technology

Energy consumption is largely determined by the cooling technology applied and is therefore a critical factor in economic and operational decisions. Electricity availability and cost are key constraints. Pad-and-fan systems and, especially, air conditioning in desert high-production systems result in high to extremely high energy use: about 330 MWh and 5,800 MWh per hectare, respectively.

4.2.2 Research component-specific conclusions

General

To the best of our knowledge, no previous study has specifically examined the effects of technological intensification on water use in greenhouse horticulture. As such, this research provides new insights into this particular field and represents a valuable contribution for entrepreneurs, knowledge professionals, and policymakers alike.

Conclusions regarding the stepping-stone model

The stepping stone model distinguishes nine archetypical production levels based on combinations of greenhouse structure, irrigation, climate control, cultivation system, and management intensity. These levels are best interpreted as conceptual reference points that structure system diversity, rather than as precise categories for individual enterprises.

For analytical clarity, the nine stepping stones were aggregated into three broader categories: low-, medium-, and high-production systems. This aggregation better captures distinctions relevant to water use.

From a water-use perspective, higher-production systems are characterised by greater irrigation demand, as well as by the growing importance of water for climate control, including fogging, pad-and-fan cooling, and air conditioning.

Conclusions from the literature review

Total water use (irrigation plus cooling) rises sharply with production intensity, averaging approximately 3,000 m^3/ha in low-production systems, about 8,400 m^3/ha in medium-production systems, and more than 40,000 m^3/ha in high-production systems.

In hot climates, cooling via pad-and-fan systems may account for more than 60% of total water use in medium- and high-production systems.

Airco systems in high-production systems can reduce water use to negligible levels when combined with drainage water recirculation and condensation recovery, but this comes at the cost of large investment and very high energy consumption.

Across studies, irrigation water use increased by approximately 143 m^3/ha for each additional kilogram of yield per square metre (excluding water use for cooling), highlighting the strong coupling between production intensification and water demand.

Data underlying this study are largely derived from controlled research environments with optimised management conditions, and therefore likely represent best-practice water use, which may underestimate actual consumption levels in commercial settings.

Conclusions from the baseline ('0') scenario

The baseline scenario demonstrates that water use in greenhouse tomato production is increasingly climate-driven. In coastal zones, irrigation remains the dominant component of water use, while cooling plays a limited role due to milder conditions that permit the use of fogging. In desert zones, cooling water constitutes a substantial share of total water use in medium- and high-production systems, and becomes dominant in high-production systems due to the necessity of pad-and-fan cooling.

Higher-production systems achieve much greater yields per square metre, but also entail higher absolute water abstraction per hectare, while water use per kilogram of tomatoes declines in the baseline ('0') scenario (particularly acutely in the coastal region scenario). This reveals a fundamental tension between absolute water use and water efficiency.

Low-, medium-, and high-production systems coexist structurally within the same regions, reflecting differences in investment capacity, knowledge, and risk tolerance. Coastal and desert regions, therefore, require fundamentally different water and climate strategies.

Conclusions from the development scenarios

In hot desert climates, further technological intensification with a constant production area leads to an increase in absolute water use of approximately 33%. When the cultivated area is expanded by an additional 10%, total water use rises by about 47%. These estimates assume the application of pad-and-fan cooling.

In relatively cooler coastal zones, technological intensification with a constant production area likewise results in increased absolute water use (approximately 27%), although to a lesser extent than in desert environments. When the cultivated area is expanded by an additional 10%, total water use increases by approximately 39%. In these calculations, cooling is assumed to be achieved through fogging systems.

Conclusions with regards to policy implications

The rebound effect associated with efficiency-enhancing technologies, commonly referred to in the literature as the Jevons paradox, is relevant to greenhouse horticulture. While technological innovations can substantially improve water-use efficiency at the farm level, they do not automatically result in lower total water abstraction at the farm and regional levels. Suppliers of water-efficient greenhouse technologies should therefore explicitly recognise and communicate the risk of rebound effects, and local authorities should take these dynamics into account when designing water management policies.

Policy frameworks that aim to steer water use solely through the promotion of efficiency-enhancing technologies are unlikely to be sufficient. Instead, complementary governance instruments are required to address absolute water use on a regional scale. Such instruments may include water area management plans, in which clear norms, allocation rules, and usage limits are established for both groundwater and surface water, as well as for different categories of users through permitting or licensing systems.

Policy instruments may further include mandatory requirements related to rainwater harvesting per hectare, incentives or obligations for the use of alternative water sources such as desalinated seawater, and restrictions on groundwater abstraction in water-stressed regions. These measures can help ensure that efficiency gains translate into less pressure on local water resources.

Continuous measurement and monitoring are essential to evaluate the real-world effects of technological upgrading and policy interventions. This includes monitoring groundwater abstraction volumes, groundwater levels, and water-quality parameters at the area level. Such monitoring enables authorities to detect unintended effects at an early stage and adjust policy instruments accordingly.

Effective water governance in greenhouse horticulture requires close collaboration between the private sector, public authorities, and knowledge institutions. Joint monitoring programmes, data sharing, and applied research can support evidence-based decision-making and help align technological innovation with long-term water sustainability objectives.

5 Recommendations

Based on the findings and conclusions of this study, the following recommendations are proposed:

1. Undertake a comprehensive integrated assessment of greenhouse development

This report constitutes a call for a comprehensive integrated assessment to determine whether the expansion of a greenhouse production area through technological intensification is appropriate and sustainable within the local context. Such an assessment should consider, *inter alia*, socio-economic costs and benefits, and potential increased pressure on natural resources, including energy, soil, surface water and groundwater, land use, and biodiversity. In this manner, potential trade-offs can be more clearly identified and understood, and it becomes possible to evaluate whether the promotion of further technological intensification through a publicly funded programme can be justified. This evaluation should not only take the form of a societal cost-benefit analysis (CBA), but should also explicitly incorporate environmental cost–benefit considerations.

2. Collect empirical data for water-efficient greenhouse systems

Future intensification of production system of greenhouse initiatives in North Africa should explicitly account for water use, both in terms of water use efficiency and absolute water consumption. Decisions regarding technological upgrades should be supported by a robust justification of the selected greenhouse technologies, cooling systems, and production periods, as these factors jointly determine water demand. Model-based analyses can provide valuable insights into expected water-use outcomes but should be complemented by empirical data from commercial practice. These empirical data should also include 'must-have' conditions, such as monitoring, abstraction limits, and water-source assessment, versus additional good agricultural practice measures. At present, reliable information from real-world operational systems remains limited and deserves further systematic investigation.

3. Unlock water efficiency gains through targeted management interventions

From both an economic and a crop production perspective, attention to water management is critically important in the context of intensifying production systems, particularly regarding the availability of high-quality source water. Substantial improvements in water-use efficiency can often be realised through relatively straightforward interventions, such as optimised irrigation control, recirculation of drainage water, and the implementation of monitoring systems. These measures may constitute 'quick wins', requiring comparatively low levels of investment while delivering significant water-efficiency gains and water savings at the farm level within the category of production system.

It is important to note, however, that in the absence of appropriate regulatory frameworks, such interventions do not necessarily result in absolute water savings. Dedicated programmes and field laboratories that specifically focus on water management should therefore be established, targeting greenhouse operators, the upstream supply industry, and governments.

4. Align policies with regional water availability

Public authorities should take explicit account of the effects of greenhouse modernisation on total regional water use when authorising or promoting technological upgrading. Efficiency improvements alone do not guarantee lower absolute water demand, particularly in water-scarce regions. Policymakers should therefore consider complementary measures to prevent uncontrolled growth in water abstraction, such as area-based water allocation limits, conditional permitting, or requirements linking production expansion to alternative water sources. Aligning greenhouse development with regional water-resource constraints is essential to safeguard long-term sustainability.

5. Analyse land sparing-related benefits and trade-offs

High-production systems can contribute to land sparing when overall production volumes remain constant, as low-productivity systems are progressively phased out. This effect is contingent upon the presence of appropriate governance structures and regulatory frameworks. While such intensification does not necessarily lead to absolute water savings in all regions, it may free up land for alternative uses, such as nature conservation. Further analysis is required to comprehensively assess these dynamics, taking into account broader socio-economic implications.

6. Foster a clearer and stronger connection between the water user and the water system

While the need for area-based water governance is acknowledged, the report addresses this primarily at a conceptual level rather than through detailed analysis. Specifically, there is no explicit linkage between water demand and regional or catchment-level water availability. Moreover, the report lacks an assessment of hydrological limits, such as groundwater recharge rates or sustainable hydrological yield thresholds, and does not provide a quantitative evaluation of impacts on aquifers or basin-level systems.

Consequently, it remains unclear whether the proposed development pathways are compatible with the carrying capacity of the water system within its spatial dimension. More robust and explicit integration between water users (e.g. greenhouse systems) and the broader hydrological system is therefore required, particularly when assessing efficiency and sustainability outcomes.

7. Further explore alternative optimisation strategies, rather than approaches predominantly driven by technological solutions

The analysis focuses mainly on technological optimisation, while largely excluding alternative optimisation strategies, such as production strategies (crop choice, seasonality), spatial planning considerations, and expansion limits. Further research that strengthens the connection between water use, water availability, and system limits would improve policy relevance and robustness for sustainable water management.

8. Undertake an environmental assessment of seawater desalination

As desalinated seawater is increasingly considered as an alternative water source, further research is required into the environmental and spatial impacts of seawater desalination based on reverse osmosis. Particular attention should be paid to energy demand and the usage of renewable energy, brine disposal, impacts on coastal and marine ecosystems, and cumulative regional effects. A more comprehensive assessment of these trade-offs is essential before desalination can be regarded as a structurally sustainable solution for greenhouse horticulture.

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To explore the potential of nature to improve the quality of life

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Report 2026-043

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This is a publication of:
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This publication was commissioned by the ministry of Economic Affairs and Climate Policy.

Netherlands Enterprise Agency | June 2026
Publication number: RVO-121-2026/RP-INT

NL Enterprise Agency is a department of the Dutch ministry of Economic Affairs and Climate Policy. that implements government policy for agricultural, sustainability, innovation, and international business and cooperation. NL Enterprise Agency is the contact point for businesses, educational institutions and government bodies for information and advice, financing, networking and regulatory matters.

Netherlands Enterprise Agency is part of the ministry of Economic Affairs and Climate Policy.