Food and Agriculture Organization
of the United Nations

UNLOCKING THE POTENTIAL OF PROTECTED AGRICULTURE IN THE COUNTRIES OF THE GULF COOPERATION COUNCIL

Regional Initiative on Water Scarcity for the Near East and North Africa

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SAVING WATER AND IMPROVING NUTRITION

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FOREWORD

The Near East and North Africa (NENA) region, including the countries of the Gulf Cooperation Council (GCC), is one of the driest regions in the world and has insufficient renewable freshwater supplies for its current population, estimated at 400 million people. With the population growing by 2 percent each year, by 2050 the region is expected to host around 650 million people – a difficult challenge for the governments of the 20 countries and territories that make up the NENA region.

Steering equitable economic and social development with a natural resource base that, at best, will remain much the same, is a challenge. However, according to accepted scientific analysis conducted by the Intergovernmental Panel on Climate Change (IPCC) and other institutions, the region's natural resource base, especially freshwater supplies, will be affected by the negative impact of climate change. Whatever the changes, it is certain that per capita access to resources will decline. Therefore, saving fresh water resources by reducing consumption is a must.

In this context, the Food and Agriculture Organization of the United Nations (FAO), in partnership with the International Center for Agriculture Research in Dry Areas (ICARDA) and the International Center for Biosaline Agriculture (ICBA) has pooled the organizations' knowledge, experience and resources to prepare a technical paper that will serve as a reference for targeted interventions implemented by the public and private sectors. The document is intended to serve as a blueprint for the region and to raise awareness and disseminate knowledge regarding new protected agriculture technologies and practices that aim to reduce water consumption in crop production. The document takes stock of current knowledge and paves the way towards more specialized studies of agricultural water-saving technologies, including high-tech closed greenhouses that minimize water loss from evapotranspiration.

This technical document was prepared as part of the Regional Water Scarcity Initiative in the Near East and North Africa (WSI), an initiative that seeks to facilitate the endeavours of governments, international organizations, civil society and the private sector to develop participatory and innovative policies for sustainable water resource governance and management, which is vital for food security in the Near East, the GCC and North Africa. Based on an accurate assessment of the available water resources, strategic decisions must be made on how to use these resources sustainably, avoiding all possible losses and reaching the best possible level of food self-reliance.

The GCC countries are looking to adopt various ways to enhance local agriculture. Switching, to some extent, from open-field production to protected agriculture is expected to save a significant amount of water, which can then be used for other purposes. This approach will offset considerably the region's constraints of limited farmland and water scarcity.

ACKNOWLEDGEMENTS

This report is the result of close collaboration between several institutions and individuals. From the outset, FAO, ICARDA, ICBA, the Ministry of Climate Change and Environment of United Arab Emirates (the) (MoCCAE), and the ministries of agriculture of all six GCC countries agreed to join forces in this effort.

The leadership and continuous support of Abdessalam Ould Ahmed, former FAO Assistant Director-General for the Near East and North Africa; Aly Abousabaa, former Director General of ICARDA; and Ismahane Elouafi, Director General of ICBA, now FAO Chief Scientist, are hereby acknowledged.

Pasquale Steduto, former Regional Programme Coordinator and manager of the FAO Regional Water Scarcity Initiative, initiated the undertaking and coordinated the work leading to the preparation of this report.

Wilfried Baudoin, former team leader of the Horticultural Crops Group (FAO headquarters), facilitated the process and contributed his experience and contacts in the area of protected cultivation. He also took an active part in bringing the report to its final format, in collaboration with Theodora Fetsi.

The first meeting, held to initiate the process of preparing the report, was convened by the FAO Regional Office in Cairo, bringing together a core group of scientists (Ayman Abou Hadid, Advanced Learning and Research Institute – ALARI, Egypt; Ahmed Moustafa, ICARDA; Martin Buchholz, Technische Universität Berlin, Germany; and Redouane Choukr-Allah, ICBA) who agreed on the scope and content of the document and identified a team of lead authors, co-authors and collaborating scientists.

Upon completion of the first draft, a consultative meeting was organized at ICBA to review the document. Azaiez Ouled Belgacem (ICARDA) and Khalil A. Ammar, Shabbir A. Shahid and Abdelaziz Hirich (ICBA) contributed to implementing the recommendations of the meeting. A second review meeting was held in Oman, hosted by the Ministry of Agriculture and Fisheries, with the support of the FAO Representation. This meeting was organised as a stakeholders' workshop with broader participation on the part of public sector authorities and private sector entrepreneurs, as well as additional resource persons from renowned universities and research centres.[1] Special thanks are due to the FAO Representative and Assistant Representative in Oman, Nora Ourabah Haddad and Hasna Alharthy, respectively, for their key role in organising that important meeting.

A final meeting was held in Cairo to integrate the recommendations made by external reviewers Feiji de Zwart (Wageningen University, Netherlands [the]) and Juan Ignacio Caballero (Institute of Agrifood Research and Technology – IRTA,

[1] These include: Sultan Qaboos University, Oman; College of Food and Agriculture Science, King Saud University, Saudi Arabia; Kuwait Institute for Scientific Research (KISR), Kuwait; College of Engineering, Qatar University, Qatar; College of Food and Agriculture, United Arab Emirates (the); Birla Institute of Technology & Science, United Arab Emirates (the); Faculty of Agriculture, Ain Shams University, Egypt; Arid Land Agricultural Studies and Research Institute (ALARI), Egypt; National Agricultural Research Center (NARC), Jordan; University of Nice, France; French National Institute for Agricultural Research (INRA), France; Technische Universität Berlin, Germany; Wageningen University & Research (WUR), Netherlands (the); and Institute of Agrifood and Technology (IRTA), Spain.

Spain), whose pertinent inputs deserve full recognition. Jean-Marc Faurès, FAO Regional Programme Leader for the Near East and North Africa, inspired the streamlining of the report and provided overall guidance in bringing it to its final format.

The ministries of agriculture of the GCC countries provided valuable country-specific information on the status of protected agriculture and on the challenges and opportunities they face in developing protected agriculture. Their vital and highly valued contribution emphasizes the timeliness of the report. Special recognition is accorded the staff of several ministries of the GCC countries for their valuable contributions, in particular Isam Mustafa Abdulrazak from Bahrain; Danah Fadel Al Ali, S. Krishna Kumar and Eissa Buhamad from Kuwait; Muthir Saleh Said Al Rawahy and Rashid Al Yahia from Oman; Hamad Al Shamari, Ali El Kharbotly, Masoud J. Al-Marri and Saud Ghani from Qatar; Abdul Mohsen Ibrahim Binsulaiman and Abdulaziz Rabeh Al-Harbi from Saudi Arabia; and Shama Abdullah Rahma Al Shamsi, Halima Yousif Hassan and Alaa N. Juma from United Arab Emirates (the).

The report was edited by Dianne Berest, Angham Abdelmageed ensured layout editing and design, Hebatallah Fahmy and Ines de la Vara provided secretarial and logistical support. Their conscious and generous contributions are highly valued and gratefully recognized.

ABBREVIATIONS AND ACRONYMS

AAAID	Arab Authority for Agricultural Investment and Development
AC	air conditioning
ADFSC	Abu Dhabi Farmers' Services Centre
ADFCA	Abu Dhabi Food Control Authority
AED	Arab Emirates dirham
AIC	Agriculture Innovation Center
ALARI	Advanced Learning and Research Institute
APRP	Arabian Peninsula Regional Program
ARASCO	Arabian Agricultural Services Company
BC	biocapacity
CF	conductivity factor
CHP	combined heat and power
CSA	climate-smart agriculture
CSP	concentrating solar power
EC	electric conductivity
ECS	evaporative cooling system
EIU	Economist Intelligence Unit
ETP	evapotranspiration
EUE	energy use efficiency
FAO	Food and Agriculture Organization of the United Nations
FGV	food gap value
GAP	good agriculture practices
GCC	Gulf Cooperation Council
GDP	gross domestic product
GFN	Global Footprint Network

GHG	greenhouse gases
GSFMO	Grain Silos and Flour Mills Organisation
ha	hectare
HADCO	Hail Agricultural Development Company
ICARDA	International Center for Agricultural Research in the Dry Areas
ICBA	International Center for Biosaline Agriculture
IPCC	Intergovernmental Panel on Climate Change
IPPM	Integrated Production and Pest Management
IRTA	Institute of Agrifood Research and Technology
IS	imported substrate
K	kelvin
KACST	King Abdulaziz City for Science and Technology
KAUST	King Abdullah University of Science and Technology
kJ	kilojoule
KFAED	Kuwait Fund for Arab Economic Development
KFAS	Kuwait Foundation for the Advancement of Sciences
KFF	King Faisal Foundation
KISR	Kuwait Institute for Scientific Research
KSU	King Saud University
KU	Kuwait University
LS	local substrate
MAF	Ministry of Agriculture and Fisheries
MCCE	Ministry of Climate Change and Environment
MENA	Middle East and North Africa
MME	Ministry of Municipality and Environment
MoCCAE	Ministry of Climate Change and Environment
MoA	Ministry of Agriculture
MW	megawatt
N/A	not available

NARES	national agriculture research and extension systems
NCARE	National Center for Agricultural Research and Extension
NENA	Near East and North Africa
NFSP	National Food Security Program
NFT	nutrient film technique
NGGH	new generation greenhouses
NH	nethouse
OECD	Organisation for Economic Co-operation and Development
PAAFR	Public Authority for Agriculture Affairs and Fish Resources
PCM	phase change material
PFWC	Planet Food World
ppm	parts per million
R&D	research and development
Rs	solar radiation
SABIC	Saudi Basic Industries Corporation
SCPD	Supreme Council for Planning and Development
SOFA	Saudi Organic Farming Association
USDA-SCS	United States Department of Agriculture Soil Conservation Service (Now USDA-NRCS, Natural Resources Conservation Service)
v/v	Volume/volume
Wh	watt-hour
WSI	Water Scarcity Initiative
WUE	water use efficiency

BACKGROUND AND RATIONALE

The Gulf Cooperation Council (GCC) is a political and economic union of Arab stated, namely Bahrain, Kuwait, Oman, Qatar, Saudi Arabia and United Arab Emirates (the). The region extends over a territory of 2 673 108 km^2 and is home to about 50 million people. The Arab region is among the most water-scarce regions in the world, with annual available water per capita falling below the United Nations' definition of water scarcity for quite some years now. It is projected that all GCC countries will experience severe water stress by the year 2025.

The combination of water scarcity, declining arable land, poor soils, a hyper-arid environment and projected climate change impacts in the region, constrain agricultural production and the capacity of the GCC countries to meet the food demands of their current and future populations. Depending on the country, the agriculture sector may use as much as 75 percent of the national available water resources. This has enormous environmental costs and significantly affects the sustainability of overall development in the Arabian Peninsula. This has raised serious concerns about food security in the food insecure but capital rich countries of the GCC, bringing food security to the fore as a primary goal in the region.

According to Al-Rashed and Sherif (2000), the lack of renewable water resources is one of the critical constraints to sustainable development in the GCC countries. Rainfall in the Arabian Peninsula is scarce and infrequent. The average annual available water per capita in the GCC countries was less than 500 cubic meters in 2001, falling below the United Nations' definition of water scarcity, and projections are bleak. By 2023, annual available water per capita is expected to decrease to 360 cubic meters. In fact, all GCC countries are projected to experience severe water stress by 2025. This is a major challenge for all GCC countries, especially as fresh groundwater is scarce and most aquifers are saline. Desalinized water is now the main source of freshwater, mainly for drinking and, recently, for irrigation.

Over-exploitation of fossil groundwater resources, mostly to meet irrigation demands and create greenery lands, has already affected the productivity of aquifers, both quantitatively and qualitatively. This is despite the fact that desalinated water is already used to cover much of the freshwater demand in the GCC countries. Reducing water consumption and increasing water efficiency are essential to enhancing agriculture and moving towards increased self-sufficiency, with the production of high-quality, safe and diversified foods. Expanding protected cultivation and exploiting its full potential should save a significant amount of water, which exploiting the full potential of protected cultivation should save a significant amount of water, which can be used to expand the production area or for other priority needs.

According to Shah (2010), the limited land and water resources in the GCC countries pose a substantial technological challenge to increasing domestic food production. Of the region's total land area of approximately 267 million ha, only 1.8 percent is currently under cultivation, mainly using groundwater for irrigation.

The total irrigated area is 1.4 million ha. Although about one-fifth of the total land area is potentially cultivable, the region's arid climate and severe biotic and abiotic stresses, including heat, salinity and lack of improved cultivars, limit the potential levels of food self-sufficiency.

Government initiatives in the GCC focus on ensuring food security through various means. Among these is the ongoing trend of investing in local food producers and manufacturers to enable them to use the latest technologies. This helps offset reliance on food imports and facilitates the implementation of food security strategies in the region.

Through different approaches, the governments of the GCC countries have implemented financial and administrative measures that favour investment in collaboration with private sector partners. These measures aim to sustainably exploit the full potential of the countries' national resources and achieve a reasonable level of food self-sufficiency, a principal pillar of national food and nutrition security strategies. Simultaneously, opportunities are being seized by the GCC countries to export commodities for which they have a comparative advantage, such as dates in Saudi Arabia. However, the countries are cautious and avoid producing agricultural commodities for export that require substantial quantities of water, which would deplete their water resources.

Being highly dependent on food imports, Arab countries are particularly exposed to severe swings in the prices of agricultural commodities. This vulnerability is likely to increase in the coming years because of high population growth, low agricultural productivity and the countries' dependence on global commodity markets. As such, the GCC countries must act urgently to improve food security. Projections indicate that dependence on imports will increase by almost 64 percent over the next 20 years. United Arab Emirates (the), for example, like other GCC countries, is highly dependent on foreign markets for its fruit and vegetable needs. It imports 62 and 47 percent of its vegetables and fruits, respectively. These very products are well adapted and responsive to protected agriculture, and their production in greenhouses could be enhanced to increase local production and self-sufficiency.

Protected agriculture is a means of production that protects crops from biotic and abiotic stress factors. Greenhouse production is considered the most water-efficient solution in the agriculture sector. For example, ICARDA studies, conducted in 2010 (ICARDA–Arabian Peninsula Regional Program [APRP], 2010), demonstrated that if the tomatoes grown in open-field production in United Arab Emirates (the) in 2007 (comprising 4 percent of the vegetables grown in open fields) had been grown under protected agriculture, about 38 million m^3 of water would have been saved. Furthermore, if the complete range of vegetables (that is, about 8 percent of the total agricultural production), was grown under protected agriculture, enough water would be saved to satisfy the water requirements of the entire date palm sector (MOCCE, 2016).

In addition to significant water savings, protected agriculture can potentially increase productivity up to fivefold over open-field production; hugely improve pest, disease and weed control; and eliminate agricultural groundwater pollution (in the case of closed soilless systems). It is evident, then, that protected agriculture is an ideal and realistic system of production under the conditions in the Arabian Peninsula as a whole, and United Arab Emirates (the) in particular, answering to the need to save water, protect the environment and supply the region with fresh, nutritious and healthy food.

Protected crop production is now a growing reality throughout the world, with an estimated 5.2 million ha of greenhouses spread throughout all the continents. The degree of sophistication and technology varies depending on local climate conditions and the socio-economic environment. The development of greenhouse production in northern Europe stimulated the expansion of protected agriculture in other areas, including the Mediterranean, North America, Oceania, Asia and Africa, with varying rates and degrees of success. This early experience showed that a mere transposition of northern European solutions to other parts of the world is not effective. Each environment requires research, development, extension, training and new norms of application to meet local requirements.

In the GCC countries, there are close to 13 000 ha of protected agriculture. Due to the hot climate in the region, many greenhouses are cooled, thus consuming large amounts of energy and water. Greenhouse energy consumption is the largest component of the system's environmental impact, particularly during the hot season (May to September). For example, annual energy consumption for greenhouse cooling in the Mediterranean region is about 100 000 kWh/ha, which leads to high energy costs. Energy consumption in the GCC, where summer temperatures are much higher than those of the Mediterranean region, is surely even greater. Goals for reducing energy consumption and increasing the use of sustainable energy sources are of great importance for greenhouse growers.

Protected agriculture is highly relevant in the GCC countries because of the harsh environment. Using different types and levels of technology, environmental and climate parameters can be controlled to enhance plant growth and product quality. Of crucial importance is the potential of saving water and increasing water productivity (litre/kg) by implementing efficient irrigation systems and reducing water loss from evapotranspiration. In addition, greenhouse cultivation is particularly suited to offset the effects of climate change since, by definition, climate parameters (including temperature, humidity, light, day length, wind and CO_2 concentration) are controlled in greenhouse cultivation (FAO, 2017).

The successful integration of greenhouse cultivation into climate-smart agriculture (CSA) depends on controlling and monitoring greenhouse gas production (GHG). GHG emissions can be reduced by reducing the energy used for heating or cooling the greenhouses and by implementing good agricultural practices (GAP) that increase productivity per unit of water, fertilizer and energy. Fortunately, many greenhouses have passive climate control systems based on natural ventilation and shading. These greenhouses do not have heating or cooling systems, which are major sources of energy consumption and GHG emissions. Even in the GCC countries, simple, tunnel-type greenhouses covered with shade nets can be used for production for about six months of the year.

In addition to the environmental and production benefits of greenhouses, further technification of greenhouse crop production in the GCC countries is expected to provide sustained employment and income for the young generation, transforming conventional farming into agricultural enterprises that use advanced automation and control climate factors and plant growth parameters.

In this context, FAO, ICBA and ICARDA have researched and produced this technical paper on the potential of protected agriculture in the region, within the framework of the FAO Regional Water Scarcity Initiative for the Middle East and North Africa (WSI). The paper was compiled through a participatory process and reflects the joint vision of the three partner institutions.

The present document is a stocktaking or baseline document that will create awareness around the potential of protected agriculture (greenhouse crop production) for reducing water consumption in the GCC countries. The document reviews the current situation of protected agriculture in the GCC countries, with special reference to cultivation practices and technologies that save water in irrigation and cooling. Furthermore, information is shared and technical specifications are provided in relation to new greenhouse technologies that can further reduce water consumption. These technologies are not yet widespread, but are under investigation in respect to their technological, environmental and economic sustainability.

It is suggested that the present study be further elaborated with a series of technical, subject-specific papers (dossiers) on selected innovative technologies and practices that have been identified for implementation in support of the technological, economic and environmental upgrading of the protected agriculture sector in the GCC countries.


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CHAPTER 1
ROLE AND ADVANTAGES OF PROTECTED AGRICULTURE

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CHAPTER 1

ROLE AND ADVANTAGES OF PROTECTED AGRICULTURE

1.1 PROTECTED AGRICULTURE WORLDWIDE AND IN THE NENA REGION

1.1.1 ORIGIN AND WORLDWIDE EXPANSION OF PROTECTED AGRICULTURE

Protected cultivation on a commercial scale appears to have initiated in Europe. The first greenhouses were considered scientific instruments for acclimatising exotic species introduced from the Mediterranean and other tropical and subtropical regions during the protectorate period. Large-scale greenhouse development was launched in the early 1950s, in Belgium and Netherlands (the). The first greenhouses were covered with glass and spread very quickly to other countries in Northern Europe and France, mostly in the green belt of major cities, including Paris, Lyon, Orleans and Angers. Shortly after that (in the early 1960s), tunnels covered with plastic film were developed in southern France. Use of these tunnels expanded very quickly due to their lower cost, lower weight and versatility. Plastic-covered greenhouses spread rapidly in other Mediterranean countries, first to Italy in the 1970s and Spain in the 1980s, and then throughout the Middle East and North Africa, in the 1990s. Plastic greenhouses developed simultaneously in the cooler countries of the Far East: Japan in the 1970s, Korea in the 1980s and especially China, from 1990 to 2000. China currently has the largest surface area of greenhouses in the world.

In the United States of America and Canada, the total greenhouse area remained very modest for a long time. Only recently (in 1990 in Canada and in 2000 in the United States of America), has there been a significant growth of glass and plastic greenhouses. In tropical and equatorial regions, protected agriculture penetrated to a significant degree, starting in the early 1990s – first in the highlands of the Andean arc (Colombia, Peru, Bolivia, etc.) and then in East Africa (Kenya, Ethiopia and other countries). In both cases, greenhouses were used mostly to produce flowers for export to Europe and North America. More recently, from the 1990s to the present, the use of tropical greenhouses has grown considerably in areas not in mid or high-altitude regions, such as China, Malaysia and India. In the early 2000s, protected agriculture began to develop in very marginal desert areas of the Arabian Peninsula.

Worldwide, the total area of protected agriculture (including small tunnels and plastic mulching) is estimated to be over 5 million hectares in 2014 (Table 1.1). Over

90 percent is located in the Far East, namely China, Korea and Japan (Lamont Jr., 2009; Kang *et al.*, 2013). The remaining 10 percent is distributed between Europe (5 percent); Africa (0.6 percent); the Middle East (1 percent); North America (0.4 percent); and Central and South America (2 percent) (Figure 1.1).

Table 1.1. Greenhouse area distribution worldwide

Country	Greenhouse area (ha)	Year	Reference
China	4 670 000	2013	Chen *et al.*, (2013)*
Egypt	16 094	2009	Ministry of Agriculture, 2009
France	26 500	2009	Tuzel and Leonardi, 2009
Greece	5 574	2013	Greek Ministry of Agriculture, 2013
Israel	26 000	2009	Tuzel and Leonardi, 2009
Italy	72 800	2009	Tuzel and Leonardi, 2009
Japan	49 049	2011	Ministry of Agriculture, Forestry and Fisheries AFF, 2011
Jordan	3 900	2013	Annual report of the Information Directorate, Ministry of Agriculture, 2013 Jordan
Kenya	8 000		Government of Kenya, GOK (2010). Agricultural Sector Development Strategy, (ASDS) 2010-2020
Mexico	11 759	2010	Secretariat of Agriculture and Rural Development (SAGARPA), 2010
Morocco	23 770	2014	Ministry of Agriculture, 2014
Netherlands (the)	10 370	2007	EuroStat, 2007
Republic of Korea	57 444	2011	Lee, 2011
Saudi Arabia	8 921	2012	Ministry of Agriculture, 2012. Statistical Year Book for 2012, General Authority for Statistics
Spain	71 698	2009	Tuzel and Leonardi, 2009
Syrian Arab Republic	4 422	2009	Tuzel and Leonardi, 2009
Turkey	49 746	2007	Tuzel and Leonardi, 2009
United States of America	8 425	2010	Hickman's North American Greenhouse Vegetable Production Statistics, 2010
Other countries[1]	80 393		
Total	**5 204 865**		

[1]Countries in Latin America, Eastern Europe, South Asia and sub-Saharan Africa

Source: *Kang et al., 2013.*

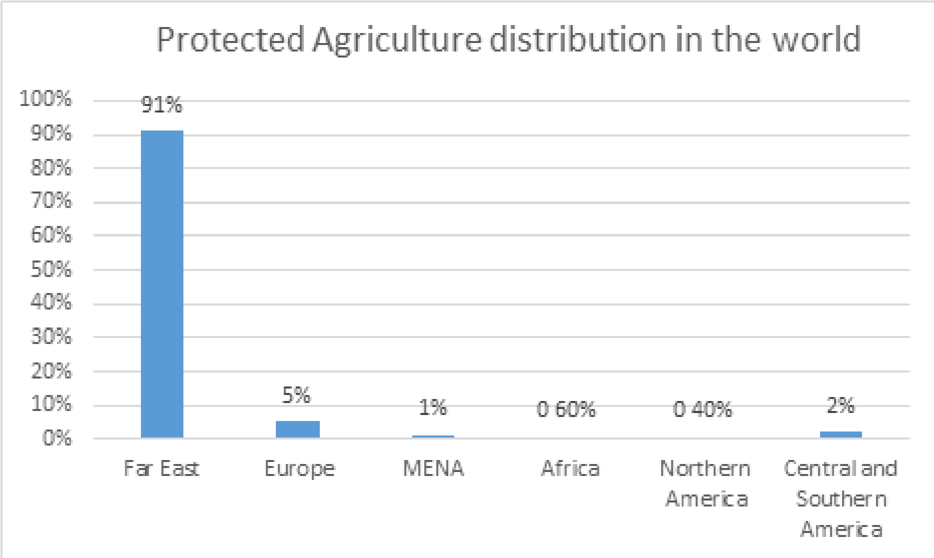


Figure 1.1 Protected agriculture distribution in the world

Source: *Kang et al., 2013.*

Globally, protected agriculture is distributed in three major climate regions: the Mediterranean (7 percent), the temperate regions of Europe, Asia and America (90 percent), and tropical and subtropical regions (3 percent). Despite the penetration of greenhouse production in warmer areas, most are located in areas with a cold season, hence the persistent problem of heating and the fluctuating and often high energy costs. The total greenhouse area in the world is limited to 400 km x 100 km, yet greenhouses contribute 60 percent of the fresh vegetables produced globally.

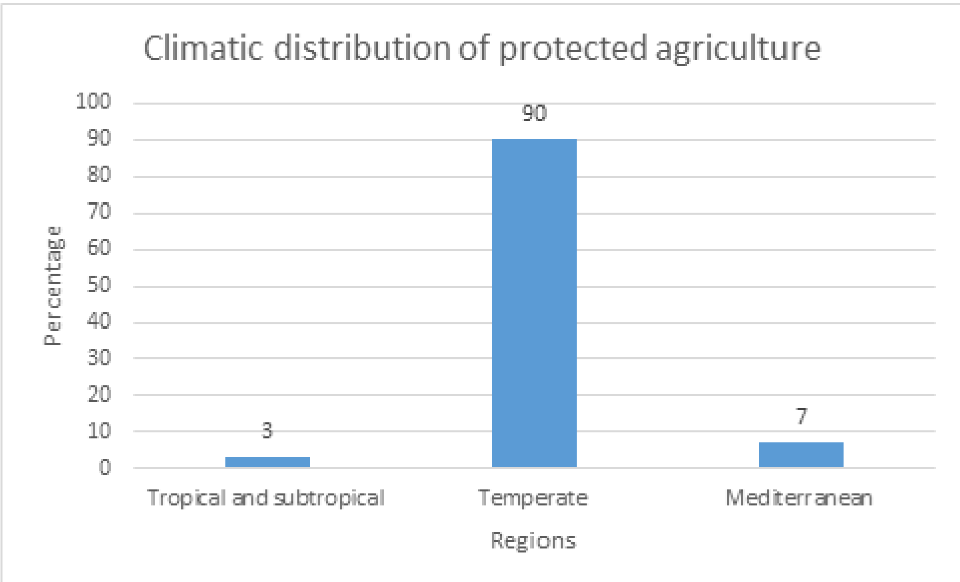


Figure 1.2 Climatic distribution of protected agriculture

Source: *Kang et al., 2013.*

The area of land covered by greenhouses is expanding rapidly throughout the world, with technologies adapted to local environmental and socio-economic variables. This trend has intensified, as greenhouse technology is perceived as a means of resilience against climate change.

1.1.2 SITUATION IN SELECTED REGIONS AND COUNTRIES

ASIA

CHINA

China has the largest area of protected cultivation, which has increased significantly in recent years. Greenhouse production in particular increased from less than 15 000 ha in 1983 to nearly 4.67 million ha in 2010, with China becoming a global leader in greenhouse vegetable production (Chen, 2013). In 2002, there was 1 963 000 ha of protected horticulture production, including 396 000 ha of greenhouse production, most of which (342 000 ha) comprised production in solar greenhouses (Son, 2007). In 2010, protected horticulture production in China accounted for over 80 percent of global vegetable production (Zhang, 2011) with a value of approximately USD 110.5 billion (60 percent of the total value of China's vegetable production). Fruits (including tree fruits such as peaches, nectarines and cherries), cut flowers and container-grown ornamentals are also grown under protection in China. Multiple types of greenhouses are used in the country with different degrees of sophistication, according to the climate and prevailing socio-economic conditions. Most are simple structures, including netted shelters, low tunnels and high walk-in tunnels (Figure 1.3). Greenhouses with advanced environmental control capability are mainly used for flower crops.

Figure 1.3 Different levels of greenhouse design and technologies

Source: *Zou & Zhang, 2011.*

JAPAN

In 1983, the plastic greenhouse area in Japan amounted to 36 951 ha (28 155 ha of which was devoted to vegetable cultivation), and the glass greenhouse area was 1 802 ha (754 ha of which was for vegetable production).

At present, Japan's greenhouse area is among the largest in the world. Japan extends a long distance from north to south through different climate conditions, in which many vegetable species can be grown in the open field in some places during some seasons. However, due to the scarcity of arable land, it is not possible to supply enough vegetables during the cold season (November through April) using outdoor cultivation. Thus, most of the supply during the cold season comes from protected cultivation. In 2015, Japan had 61 503 ha of vegetable cultivation in tunnels. Cut flowers and fruit cultivation (particularly citrus fruits) in greenhouses and under other protective facilities has been expanding. Protected cultivation of vegetables is now making a great and indispensable contribution to the Japanese diet.

The bulk of the greenhouses are covered in plastic film. (Less than 5 percent of the greenhouses are glass-clad.) Sixty-nine percent of the total greenhouse area is used for vegetable production, only 17 percent for flowers, and 14 percent for fruit tree production. Three-fourths of the crops grown hydroponically are vegetables.

SOUTH KOREA

The total area of protected vegetable cultivation in South Korea was 81 600 ha in 1995. This increased to 86 400 ha in 2000, with a total yield of 3 291 000 tons (Fang *et al.*, 2005). In 2007, there was a total of 52 000 ha of greenhouse production, 24 percent of which was produced in heated greenhouses (Montero *et al.*, 2011). Vegetables comprise the majority of the crops under protected cultivation (93 percent), with the rest being flowers. Around half (54 percent) the total flower production area consists of protected cultivation (a greater percentage than that of any other horticultural crop). Finally, 49 percent of protected flower cultivation consists of cut flowers and container plants (Son, 2008).

NORTH AMERICA

UNITED STATES OF AMERICA

The greenhouse vegetable industry in the United States of America revolves around the production and marketing patterns of vegetables grown in the open field. A major proportion of greenhouse production concentrates on winter production of tomatoes, when the quantity and quality of field-grown tomatoes drop and prices are high. The mid-winter price slump (February through March) appears to correspond to the peak production period in Mexico, when large volumes of tomatoes from Mexico flood the markets of the United States of America. The summer price decrease (July through October) is due to competition from high-quality tomatoes grown in Texas and California and those grown by backyard gardeners.

Growers in the United States of America claim that the economic rewards of fruit and vegetable greenhouse production are not as lucrative as those of other related agricultural ventures, such as greenhouse foliage production. Rising fuel costs, for example, present a major problem to growers. Other difficulties are the lack of marketing experience of some growers and the high degree of skill needed to successfully grow above the break-even point under intensified greenhouse conditions. Due to these and other factors, many new greenhouse vegetable growers are not successful. Although the greenhouse vegetable industry is again expanding, the competitive position of firms remains at a disadvantage. Increased competition from alternate supply sources and rising greenhouse production costs under a relatively elastic demand situation appear to be the causes of the competitive disadvantage.

CANADA

Canadian production is concentrated in Ontario, British Columbia, Quebec and Alberta. Ontario and British Columbia account for 90 percent of Canadian production, with Ontario producing 66 percent and British Columbia producing 24 percent. Greenhouse size ranges from 0.2 ha to 18 ha. Modern Dutch Venlo-style glass greenhouses are used primarily by the industry in the Lower Mainland and are well suited to the region's moderate climate and lower light levels. Ridge and gutter poly greenhouses predominate in the Interior, Northern and Island regions because they provide a higher isolative advantage for colder regions and are more cost-effective for the smaller growers in these areas. Larger greenhouses have sophisticated computerised climate control systems that continuously monitor and regulate temperature, light, humidity, irrigation and nutrient levels to optimize plant growth.

Over the last 20 years, many greenhouses have used double inflated polyethylene, which showed greater cost savings in construction and maintenance. However, as the economy began to change in 2004, the price gap narrowed, year-round production demand increased, and Canada saw a return to glass houses instead of poly.

The most common form of heating is natural gas-fired hot water boilers. Liquid carbon dioxide and carbon dioxide extracted from boiler flue-gas condensers are used to supplement carbon-dioxide (CO_2) levels in the crop.

The principal crops grown include tomato (beefsteak and tomato on the vine [TOV], or cluster), sweet bell peppers (red, yellow and orange), long English cucumbers, and butter lettuce. Crops are grown hydroponically in soilless media (mostly in sawdust) with drip fertigation systems.

EUROPE

In Europe, the protected agriculture surface area was estimated to be around 200 000 ha in 2013 (Table 1.1), 85 percent of which was in Spain, Italy and France (Baeza *et al.*, 2013; Castilla *et al.*, 2010); 5 percent (10 000 ha) in Netherlands (the) and 2.8 percent (5 574 ha) in Greece.

NETHERLANDS

Dutch greenhouses are generally multi-span, with a fixed span width and a glass cover with a slope of about 25°, and fully automated roof ventilation (Venlo design). These greenhouses are fitted with automatic climate control (heating and ventilation) and carbon dioxide fertilisation. They consume considerable amounts of energy. What has kept Dutch greenhouse horticulture profitable for the past few years has been the electricity produced by co-generator engines, the waste heat and CO_2 of which are used in the greenhouses (Baeza *et al.*, 2013).

According to Aalsmeer, HortiFair/ Bleiswijk (2011), Dutch growers have made agreements with the government stipulating an annual reduction of 2 percent in energy use per unit of produce, expecting a 50 percent reduction of CO_2 emissions by greenhouse enterprises between 1990 and 2020, with 20 percent of the energy consumption in Dutch greenhouses coming from sustainable energy sources by 2020. Numerous experiments have been carried out over the recent years. The research has demonstrated that it is possible to save 30 percent or more on the use of fossil fuels without negatively impacting production or quality (Aalsmeer, Horti Fair/ Bleiswijk, Wageningen UR Greenhouse Horticulture, 2011).

MEDITERRANEAN REGION

In the Mediterranean region, the greenhouse industry is mostly devoted to growing edible vegetable crops, accounting for 84 percent of the greenhouse area in Italy, nearly 90 percent in Spain, and 92 percent in Greece (Castilla, 2002). The area of greenhouses dedicated to producing ornamental plants is in a much weaker position and often unable to compete with Netherlands (the) in this sector.

In Spain, the main vegetable crops grown in greenhouses are tomato, sweet pepper, cucumber, green beans, strawberry, melon, watermelon, eggplant, squash and lettuce, in descending order (Castilla and Hernandez, 2005). The production of flowers (mainly carnations and roses) and ornamentals constitutes only around 5 percent of the greenhouse area. Banana is the major tree crop, and the area of table grapes under temporary plastic cover in the south-east of the country is increasing (Castilla and Hernandez, 2005).

Low-cost greenhouses are the main type of greenhouse used in the Mediterranean region. Growing in low-cost greenhouses with only passive climate control always involves limiting high-quality production during certain periods of the year, but the investment costs of this type of greenhouse in mild winter climates are around 10 percent those of a standard glasshouse in Netherlands (the) (Baeza *et al.*, 2013).

TURKEY

Turkey has one of the larger areas of protected cultivation in the region. Protected cultivation includes glass- and plastic-covered greenhouses, as well as high (walk-in) and low plastic-covered tunnel greenhouses. The total protected cultivation area reached 78 960.4 ha in 2019, with 28.42 percent (22 440 ha) under low plastic tunnels, 14.06 percent (11 103.8 ha) under high tunnels, 9.56 percent (7 549.5 ha) in glasshouses and 47.96 percent (37 867 ha) in polyethylene-covered greenhouses (Turkish Statistical Institute, 2020). Eighty-five percent of the protected cultivation area is located on the southern coast of the country, next to the Mediterranean Sea, where climate conditions are favourable for protected cultivation, without requiring additional heating. In this region, Antalya is the most important protected cultivation centre with 28 652.2 ha. A wide diversity of crops are grown under protected cultivation, including vegetables (96 percent), ornamental crops (3 percent) and fruits (1 percent). Of the total protected cultivation area, 87.5 percent is covered with plastic film and the rest with glass. Turkey has the advantage of having alternative energy resources, predominantly geothermal energy. As a result, construction of high-tech greenhouses has increased in areas where geothermal water resources are available. Even though there are significant differences among the greenhouses in terms of design and climate control, overall important improvements have been achieved in new cropping technologies since the end of the 1990s. These include improved quality of seedlings, particularly through grafting, the use of soilless culture, and widespread implementation of good agricultural practices. The greenhouse sector is commercially successful, building on a long tradition of horticultural exports to the Middle East, Romania, Russian Federation (the) and the Ukraine. Yields are high in the country's modern greenhouses.

ISRAEL

Greenhouse production of vegetables in Israel has soared in the last 20 years. The use of plastic greenhouses, especially for vegetable production, has made an oasis out of the desert in many parts of Israel. One such example is the proliferation of greenhouse vegetable and flower production in the Arava Desert (Cantliffe, 2006). Production under protected conditions has become the principal way for Israeli growers to ensure a constant, year-round supply of high-quality products, while minimising the use of chemicals. This type of production helps overcome obstacles posed by adverse climate conditions and a shortage of water and land. The current workforce shortage, especially of foreign workers, which may impact production outputs by as much as 20 percent, presents a threat to protected production and a challenge to the nation at large.

The total area covered with greenhouses, shade-houses and walk-in tunnels increased from 900 ha in the 1980s to about 26 000 ha in 2012 (an average annual growth of 4 to 6 percent); with 12 000 ha of vegetables and 5 000 ha of floriculture; 6 000 ha of low tunnels for melon, watermelon and strawberries; and another 2 500 to 2 900 ha of fruit trees (mainly nethouses). The average farm size is 4 to 8 ha for vegetable production and 8 ha for flower production. Israeli farmers successfully grow between 85 and 100 tons of sweet peppers each season per hectare of greenhouses, and today the yield in nethouses reaches 80 tons, 90 percent of which is slated for export. Under protected agriculture, an average of 400 tons of tomatoes are grown per hectare, four times the amount harvested in open fields, and about 280 tons of short cucumbers are produced per hectare. In addition to flowers and vegetables, which have been grown in greenhouses in the last few decades, fruits such as grapes, pomegranates and citrus, are now grown in plastic and net-covered greenhouses for hail protection, water savings and improved quality.

Substrate culture systems are widely used in Israel (Figure 1.4). At present, the total area of substrate-based production is over 1 000 ha. In recent years, approximately 25 percent of greenhouses with soilless substrates have been switched to recycled irrigation systems. Recycling the water and nutrients by reusing water drainage in the same or nearby fields appears to be the most efficient, environmentally sound and economical solution, saving approximately 30 to 40 percent of water and fertilizer.

Figure 1.4 Intensive soilless culture systems

Source: *Source: Avidan, and Haifa-group, 2012.*

NENA REGION

Protected agriculture was introduced in the NENA region to take better advantage of the mild winter climate of the coastal lands along the Atlantic Ocean and the Mediterranean Sea. At present, there are almost 71 297 hectares of protected agriculture in the region (Table 1.2). Successful vegetable crops are grown as fall-winter and spring-summer crops. In Algeria and Tunisia, most of the production is destined for local fresh markets, while in the remaining countries most of the produce is shipped to Northern European markets and the GCC countries.

Table 1.2 Surface area of protected agriculture in the NENA region

Country	Surface area (hectares)	Source
Algeria	5 800	Department of Agricultural Services, 2013
Egypt	16 094	Agricultural Economic Affairs Sector, Ministry of Agriculture, Egypt, 2014.
Jordan	4 028	Muien Qaryouti, 2014
Lebanon	3 760	Muien Qaryouti, 2014
Libya	5 000	Tuzel and Leonardi, 2009
Morocco	23 770	Ministry of Agriculture, 2014
Syrian Arab Republic	5 105	Muien Qaryouti, 2014
Tunisia	7 740	Ministère de l'Agriculture, des Ressources Hydrauliques et de la Pêche, 2015
Total	**71 297**	

MOROCCO

Protected cultivation in Morocco is based on unheated greenhouses. The estimated area of protected culture is almost 24 000 ha, including vegetable, cut flower and fruit production. The main vegetable crops are tomatoes, melons, watermelons, peppers, green beans and strawberries. Roses and carnations are the leading cut flowers, and bananas and grapes are the major fruit crops. Presently, the protected cultivation industry is developing in different parts of Morocco with specialized areas. The trend is to switch from hemi-cylindrical Quonset-type plastic greenhouses to the Canarian-type plastic greenhouse structure. Most of the protected cultivation is concentrated along a narrow, relatively frost-free area of the Atlantic coast between Larache and Agadir and as far as Dakhla, which receives abundant light from October to March (from 1 150 to 1 400 hours). Morocco has had great success growing bananas in greenhouses, and there is a trend to extend the technology to other fruit crops, including raspberries, blueberries, blackberries and fruit trees, to protect them from hail and bird damage. The fruit trees grown in protected conditions include table grapes, apples, nectarines, plums and peaches.

TUNISIA

Vegetable crops grown in open fields and under plastic cover occupy an approximate surface area of 140 000 ha in Tunisia. Currently, protected crops occupy about 5 percent of the area for vegetable crops, but their production, estimated at 400 000 tons, represents about 14 percent of the volume of vegetable production and 20 percent of its value. Protected cultivation also provides economic and social value by valorising small landholdings and by creating from 400 (melon) to 1 000 (tomato) days of employment per hectare for protected crops, compared to 150 to 200 days per hectare for open-field crops. In 2013, these crops provided estimated foreign exchange earnings of TND 60 million (approximately USD 36.8 million), 3 percent of the value of agricultural and agro-food exports.

The area of vegetable crops under protected cover (Canarian-type greenhouses, multi-span greenhouses and small and walk-in tunnels) represents some 7 740 ha, comprising:

- Unheated greenhouses (1 490 ha): Hot pepper remains the main species grown in unheated greenhouses, occupying 56 percent of the area; followed by tomatoes, occupying 26 percent of the area; and melons, occupying only 6 percent of the area. Monastir governorate alone accounts for about 39 percent of the area of vegetables grown in unheated greenhouses (572 ha), followed by the governorates of Sidi Bouzid, Mahdia and Sfax, with 14.3 percent, 13.2 percent and 12.7 percent, respectively.
- Small tunnels (6 000 ha): The main produce cultivated in small tunnels are watermelon and hot peppers. Together, they occupy 4 178 ha, or 57 percent of the total area of small tunnel production. The governorate of Sfax is the main producer of vegetables in small tunnels.
- Geothermal heated greenhouses (250 ha): Vegetable crops under greenhouses, heated by geothermal waters, are located in three governorates: Kebili, Tozeur and Gabes.

A five-year plan has been formulated to boost greenhouse development and installation. Under this plan, it is expected that by 2020, 51 550 additional tons of food crops (80 percent being tomatoes) will be produced. Fifty-four percent of this additional production (27 840 tons, again, mainly tomatoes), will be exported, bringing the total volume of exported crops to almost 41 000 tons – three times the volume exported in 2013.

ALGERIA

According to the Ministry of Agriculture and Rural Development (2013), the greenhouse area grew from 20 ha in 1970 to 5 800 ha in 2013. In 2012, the Department of Agricultural Services in Biskra (2013) estimated the greenhouse area to be 3 079.76 ha – an increase of 528.52 percent in 20 years. In 2010, Algeria produced 7.8 million tons of vegetables, through open-field and protected cultivation (FAOSTAT, 2010). This was twice the amount of vegetables produced in 2000. In 2010, the most important crops produced were potatoes (3.3 million tons), dry onions (1.1 million tons), watermelons (0.95 million tons), and tomatoes (0.58 million tons). However, the level of productivity is still very low compared to the other countries in the NENA region. Several measures could be taken to increase production, one of the most important of which is to improve horticultural practices through training, including training in choosing adequate hybrid varieties, in fertigation and in adequate pest control.

EGYPT

In Egypt, limited water resources and rapid population growth were the major factors that drew attention to the option of intensive, protected agriculture. The total area of protected agriculture in the country is 16 094 ha, and the major crops are peppers, tomatoes, cucumbers, cantaloupes, beans, strawberries and melons (Ministry of Agriculture of Egypt, 2014). Egypt has the potential to become an exporter of tomatoes, cucumbers and peppers. However, it is not yet clear whether the country will be able to compete price-wise with Spanish producers during the winter season. In order to do this, the country could maximise the market windows, producing a product of guaranteed high quality during periods of limited supplies. Egypt produces over 40 types of fruits and vegetables on about 800 000 ha of land. The horticulture sector has been continually expanding since 1987.

Protected crops are now grown in more than 61 817 polyethylene greenhouses (including high tunnels), the average size of which is 570 m^2 (8.5 x 86 m). Additionally, Egypt has approximately 4 032 ha of glass greenhouses. Traditionally, Egypt's exports comprise green beans, potatoes, onions and citrus fruits. In recent years, however, the country's exports of strawberries and seedless table grapes have been booming. Egypt is the world's seventh largest exporter of green beans, with 8 percent market share. (Kenya is the largest exporter, at 19 percent, followed by Morocco, at 17 percent.) Egypt is the main exporter of green beans to Netherlands (the), with a market share of 25 percent, just ahead of Spain (24 percent) and Kenya (20 percent) (HEIA, 2003).

JORDAN

Jordan has the potential to export tomatoes, cucumbers and peppers. The country could produce high-quality produce, which it could export to the GCC countries, maximising the market windows during periods of limited supplies. Jordanian production is concentrated in the highlands (85 percent), with the rest located along the Jordan River (15 percent). In the past ten years, greenhouse production of vegetables more than doubled from 1 600 ha in 2004 to 3 900 ha in 2013. Most of the greenhouses are walk-in tunnels (91.3 percent), and the rest are multi-spans (Figure 1.5). The main crops grown in greenhouses are cucumbers, covering 52.3 percent of the protected area, tomatoes (21.6 percent) and sweet peppers (13.3 percent). The average yield per square meter of cucumbers, tomatoes, sweet peppers and strawberries is 13.2, 15.1, 6 and 2.2 kg, respectively.

Figure 1.5 Principal greenhouse types in Jordan

Source: *Choukr-Allah, 2016.*

LEBANON

The total greenhouse area in Lebanon is about 3 760 ha, sown with tomatoes, cucumbers and melons. Most of the protected agriculture (41 percent) is located in the Akkar region, followed by the Southern region (16 percent), Mount Lebanon (14 percent), and Northern Lebanon (13 percent). The crops grown under greenhouses are tomatoes (35 percent of the cultivated area), cucumber (22 percent), squash (9 percent), melon and watermelon (8 percent), and green beans (7.2 percent).

1.1.3 PROSPECTS FOR THE FUTURE OF PROTECTED AGRICULTURE

The twenty-first century has brought more people, less water and more global demand for food. Vegetable growing, with its importance for human nutrition, has undergone many production changes in the past 100 years. Science has taught farmers how to intensify their efforts, giving them the luxury, and the curse, to over-produce. The growing population, as well as continuous dwindling freshwater resources, will put pressure on farmers to reduce the use of fresh water for agriculture, forcing them to use marginal waters.

Protected agricultural systems in warm-winter climates will surpass much of the open field production of today. The use of soilless systems and improved pest management are improving water and nutrient efficiency in protected agriculture.

Worldwide greenhouse production is far from reaching its full potential, and the control of the climatic variables that it provides can act on the main production parameters.

The choice of technological equipment for greenhouses should be directed towards a sustainable production system. Protected agriculture is no longer limited to vegetable production in mild-winter climates. It has been extended to very cold climates as well as hot and desert areas and is also expanding in subtropical and tropical regions. Moreover, protected agriculture is now used not only for vegetable production but to produce fruits, fish and algae.

Breeding programmes to maximise the efficiency of protected agricultural systems are likewise essential. Plant growing structures must conform to the needs of plant productivity, as well as production and water economics. Most importantly, agricultural systems based on open-field production in places such as North America, Mexico and the Middle East must be prepared to change to more intense protected agricultural systems in as little as five years. The future for year-round, efficient and economical production through protected agriculture will depend on these science-based changes.

1.2 ROLES AND ADVANTAGES OF PROTECTED AGRICULTURE

From 2007 to 2009, when the food price crisis was magnified by the financial crisis and a global economic recession, the number of people suffering from hunger and undernutrition in the world increased significantly, reaching a peak of more than 1 billion persons in 2009 (FAO, 2011). As a result, the world witnessed a rise in export restrictions by trading partners. This greatly affected the countries of the Arabian Peninsula, especially the six GCC countries – the world's major food importers. As the cost of food supplies from outside the region rose, local food supplies decreased due to low productivity and severe water scarcity (a process which continues today). Meanwhile, demand for food in the region has risen because of the increase in the population, which is expected to double from 2000 to 2030 (Woertz, Lippman, Wilcox & Boucek, 2010).

Stakeholders are being forced to shift towards modern crop production technologies, such as protected cultivation, because of population growth, climate change, smaller landholdings and increasing pressure on natural resources such as land and water, combined with high demand for high-quality fresh produce. At least some portion of the present area under open-field vegetable cultivation must be converted to protected cultivation to increase national productivity and the quality of the produce. Promoting protected cultivation will create a considerable number of jobs for unemployed educated youth, and improve national economies through the sale of high-quality produce on the domestic and international markets.

Protected agriculture is an advanced agricultural method and an effective option for improving and intensifying agricultural production in terms of both quantity and quality. Protected agriculture is an industrial type of agriculture, which allows year-round crop production based on different levels of technology and climate control features, requiring capital investment. Studies have shown that, compared to open-field cultivation, protected agriculture can save up to 50 percent of irrigation water and up to 30 percent of fertilizer. It can also double or triple productivity and yield per unit of area and unit of water.

Protected agriculture has shown great potential for producing the highly nutritious fruit and vegetable crops that are essential for a healthy and balanced diet. ICARDA's research has shown that, in the Arabian Peninsula, using protected agriculture with its associated modern techniques, such as soilless culture (hydroponics) and integrated production and pest management (IPPM), can substantially increase water productivity, with little or no use of agro-chemicals. Although soil is the most available growing media, providing anchorage, nutrients, air and water to the plants' rooting system; in-soil cultivation poses serious limitations for plant growth. These include diseases caused by pathogens and nematodes in the soil, unsuitable soil reactions, salt accumulation due to irrigation, unfavourable soil compaction, poor drainage, degradation due to erosion and other issues (Moustafa, 2010). Expanding protected agriculture would save considerable amounts of water and land that could be used for other field crops and food production activities (Moustafa *et al.*, 1998).

As compared to conventional cultivation, closed-soilless production systems inside greenhouses can save up to 50 percent of water consumption in the production of vegetable crops and ornamental and medicinal plants.

Protected agriculture can also provide fresh vegetables outside their natural production season, thus securing the production of vegetables despite the conditions of the natural environment. Furthermore, productivity per unit area in greenhouses is much higher than in open-field agriculture. Agricultural production can be intensified 200 percent using modern protected agriculture technologies. This provides an opportunity to reduce food imports, improve self-reliance and eventually export surplus production, with consequent hard currency savings.

Protected agriculture is one of the ways to mitigate the effects of adverse weather conditions and limit their impact on crop productivity. Non-seasonal production also ensures a higher price. However, protected agriculture involves additional costs in terms of production inputs, including the greenhouse structure and plastic, fiberglass or glass covers. As the production of crops in the off-season is very profitable, off-season producers must target for increased productivity and improved quality in order to face up to strong competition in the consumer markets from imported products such as tomatoes, cucumbers, green beans, strawberries and ornamental flowers. In the GCC countries, crops can be produced during the winter season in simple, low-cost greenhouses without heating or cooling, giving the region a relative advantage in cultivating these crops. Because of this advantage and given increasing water demand and scarcity, the GCC governments have recognized the importance of protected agriculture in rationalising water consumption and improving the quantity and quality of local production.

The success of pilot growers using protected agriculture has encouraged the national agricultural research and extension systems (NARES) to continue to support such initiatives. For example, in United Arab Emirates (the), the Ministry of Climate Change and Environment (previously the Ministry of Water and Environment) is supporting growers by covering 50 percent of the cost of their greenhouse and soilless production systems and providing training in greenhouse management, especially in irrigation water management. The governments of the GCC countries are expected to increase the area under protected agriculture in the future in order to contribute to food security.

1.2.1 ECONOMIC CONSIDERATIONS IN SUPPORT OF PROTECTED AGRICULTURE

GCC countries are keen to reduce their reliance on foreign supply of essential food items and increase their level of food self-sufficiency, particularly for economically viable options. Protected agriculture has numerous economic benefits: the opportunity for off-season vegetable production, fetching higher market prices; the high level of productivity; the large increase in revenue and profits due to the short capital cycle; and the benefit of selling the produce promptly. Because of these multiple benefits, governments have been keen to provide financing to help farmers further develop protected agriculture.

It is important to bear in mind that protected agriculture requires greater investments to cover the additional costs, as compared to open-field production. A study on the comparative advantages of the tomato production systems of Syrian Arab Republic (the) (Atiya, 2006) indicated that the total cost of greenhouse production systems was over twice that of open-field systems. The results also showed that fixed costs of greenhouse tomato production systems were 1.5 times higher than those of open-field systems, due to the additional cost of greenhouse construction.

However, studies also demonstrate the benefits of protected agriculture in terms of yield and profit. In Turkey, protected cultivation of bananas was found to have a comparative advantage over open-field cultivation, expressed as the number of hands and fingers per bunch as well as bunch weight. Average annual yield under plastic greenhouse production was 53 percent higher than open-field production (65.5 tonnes/ha^{-1} compared with 42.8 tonnes/ha^{-1}) (Gubbuk and Pekmezci, 2004).

A comparative analysis of greenhouse versus small-scale open-field tomato production was carried out in Nakuru North district, in Kenya (Mwangi, 2012). The results indicated that the mean income for greenhouse tomato growers was almost twice that of open-field tomato growers. Moreover, net profit per square meter and gross margin per square meter for greenhouse tomato farmers were found to be ten times higher than those of their open-field counterparts. The study also found that for efficient and effective adoption of greenhouse technology for tomato production, it is necessary to address education, credit and infrastructural improvement issues.

Greenhouse technology has been proved profitable and preferable to open-field systems elsewhere in the world as well. Studies standardize gross margins and net profit per square meter to enable the comparison between both production systems.

In Tamil Nadu, India, an economic analysis of tomato production was carried out by Ganesan in 2002. Ganesan used yield and quality as the study parameters and looked at the performance of naturally ventilated greenhouse tomatoes compared with open-field tomatoes. By using the number of fruits per plant, individual fruit weight and total yield per plant, the study showed that greenhouse tomatoes had significantly higher yields than those grown in the open-field system. Further, among the different greenhouse types studied, greenhouses with ventilation gaps in four sidewalls and greenhouses with ventilation gaps in a triangular roof were found to be the best for tomato cultivation. By using economic comparative analysis, the study concluded that greenhouse tomatoes gave better results and were more suitable for the study area than open-field tomatoes.

Yields have also been used in economic analysis to evaluate elite tomato varieties in the semi-arid regions of Eastern Kenya by Musyoki *et al.* (2005). In those studies it was found that higher yields are generally possible, especially with greenhouse technology (Cook, R. & Calvin, L., 2005).

Although there are some limitations in greenhouse farming, overall, greenhouse production seems to be more profitable, with farmers earning ten times more than in open-field production. One aspect that contributes to this is the reduced amount of water and chemicals used in greenhouse production and the increase in yield. One study concluded that both production costs and yield were higher in polyhouse-type greenhouses than in open-field production. In another study, Parveen and Grover (2012-13) compared the economics of cucumber cultivation in greenhouses and in open-field conditions in Haryana and concluded that the cost of cultivation of cucumber under polyhouses was higher than that of open-field production and provided significantly higher yield. In tomato production, yield was more than three times higher in greenhouses than in open-field production and the market price of the tomatoes produced in greenhouses was higher than that of the tomato produced in open fields. Tables 1.3 and 1.4 provide examples comparing the cost-benefit ratio of greenhouse and open-field production in India.

Table 1.3 Costs of tomato production in greenhouses and in open-field farming in India during the 2013 growing season

Item No.	Production and marketing cost variable	Greenhouse (USD ha^{-1})	Open field (USD ha^{-1})
1	Field preparation and cultivation	219	237
2	Seed	729	729
3	Fertilizers	802	146
4	Irrigation	146	200
5	Plant protection	124	292
6	Rental value of land per year	1 276	1 276
7	Total labour, including harvesting and crop maintenance	2 916	1 531
8	Marketing cost (transportation, packaging, loading and unloading, etc.)	1 422	583
9	Total production and marketing cost	7 634	4 994

Source: *Primary survey (Pardeep, 2016).*

Table 1.4 Cost-benefit analysis for greenhouses and open-field production in India

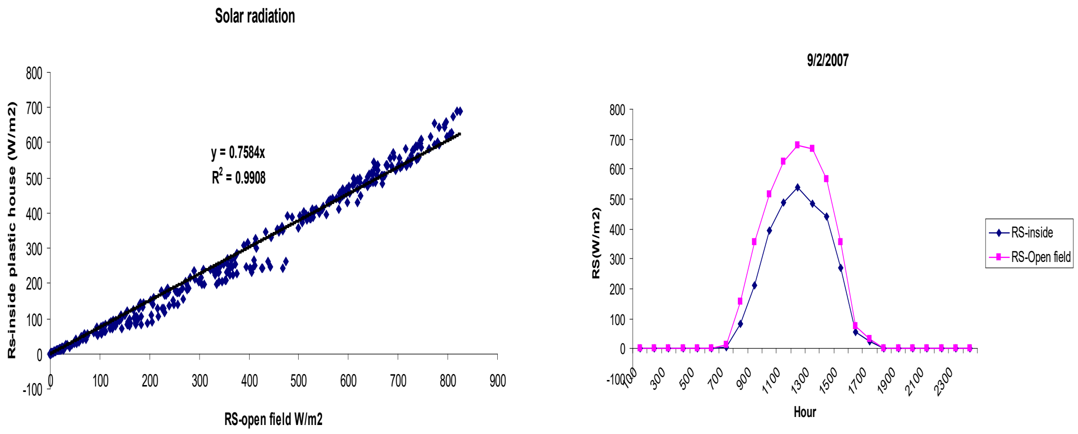
Elements of comparison	Greenhouse	Open field
Total production in a year (kg ha^{-1})	833 333	26 190
Average market selling price (USD ha^{-1})	0.367	0.245
Total revenue per year (USD ha^{-1})	30 622	6 416
Total cost per year (USD ha^{-1})	7 633	4 994
Total benefit per year (USD ha^{-1})	22 988	1 423

Source: *Pardeep, 2016.*

1.2.2 WATER CONSUMPTION AND CROP PRODUCTIVITY

Most experiments and observations have shown that crops grown inside greenhouses consume less water than those grown in the open field. This is due to the different weather conditions of each type of production. Plants consume more water when the temperature of their leaves is different than that of the surrounding air. When the air temperatures rise from 8 °C to 18 °C, water consumption increases by 118 percent, and when the temperature of the leaves increases from 18 °C to 24 °C, water consumption increases by 33 percent (Al-Faraj *et al.*, 1994). In protected agriculture, the temperature of the plants' leaves can be used to estimate water consumption and to determine precise irrigation scheduling. Mazahrih *et al.* (2001) found that water lost through evaporation in unheated greenhouses in the central Jordan Valley was between 0.22 and 0.50 percent the amount of water lost through evaporation in the open field, depending on the type of crop grown.

Net solar radiation is one of the most important climatic elements needed to estimate the water consumption of crops grown inside greenhouses. The solar radiation (Rs) inside non-cooled greenhouses is 25 percent lower than it is in the open field, due to the GH cover (Figure 1.6). Since evaporation in protected production is up to 70 percent less than the evaporation in the open field (Stanghellini, 1993), the water needs of crops under protected cultivation are very low. Also, wind speed is close to zero inside greenhouses, contributing to the low water vapour pressure deficit near plant leaves, which reduces both transpiration and evaporation. Finally, the relative humidity inside greenhouses is higher than in the open field. When combined, these conditions reduce the water consumption of plants in greenhouse production by more than 50 percent compared to open-field production (El Moujabber *et al.*, 2001) and increase production between two and three times that of open-field agriculture.



(a) Solar radiation during the growing season (b) Solar radiation during the day

Figure 1.6 Solar radiation inside greenhouse and in the open field in the Jordan Valley during the 2007 growing season

Source: *Campbell Scientific Meteorological Station (CR10x data logger), 2007.*

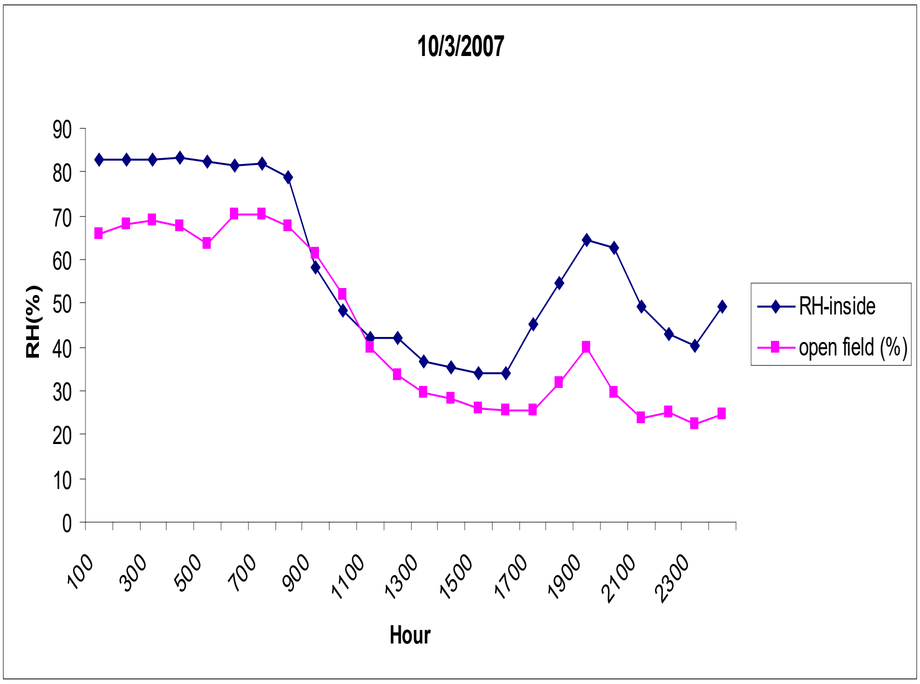


Figure 1.7 Air relative humidity (RH percent) inside the non-cooled greenhouse and in the open field in the Jordan Valley during the 2007 growing season

Source: *Campbell Scientific Meteorological Station (CR10x data logger), 2007.*

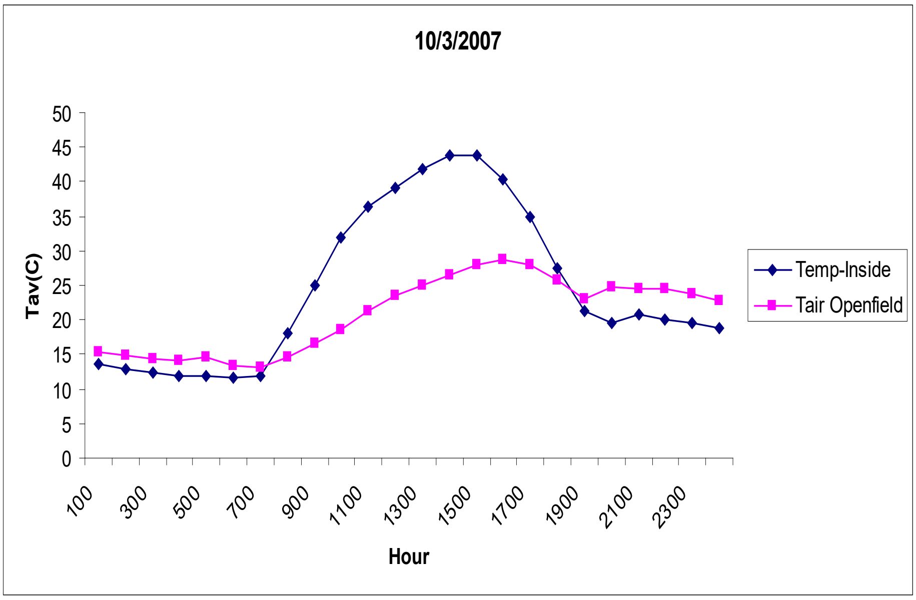


Figure 1.8 Average temperature inside the greenhouse and in the open field in the Jordan Valley during the 2007 growing season

Source: *Campbell Scientific Meteorological Station (CR10x data logger), 2007.*

The use of protected agriculture improves water productivity significantly over that of open-field farming (Stangellini, 1993). Crop water use efficiency (WUE) is often used to express production (photosynthesis, biological or economic) for each unit of water (evapotranspiration or added water) as described by Howell (1990). The water productivity of tomato in the open field is estimated at 20 kg/m^3. This can increase to 35 kg/m^3 when using simple protected agriculture. Using soilless agriculture, productivity per cubic meter increases to more than 65 kg/m^3. On average, WUE in protected cultivation, combined with soilless culture, is three to six times that of open field cultivation. This variation in crop water use efficiency is a strong motivation for investors to adopt protected agriculture, not only to save water but also to increase production and save on production inputs such as composting, energy and labour. As to the component of agricultural land-use, the production rate per unit area in greenhouses is 200 to 300 percent greater than that of crops grown in the open field.

Table 1.5 Water use efficiency (WUE) of tomato crops grown under different climatic conditions and using different growing systems

Growing conditions	Country	WUE (Kg/m^{-3})
Open field	Israel (soil culture)	17
	France (soil culture)	14
	GCC (soil culture)	2.8
Unheated plastic greenhouse	Spain (soil culture)	25
	France (soil culture)	24
	Israel (soil culture)	33
	Italy (Open substrate culture)	23
	Italy (Closed substrate culture)	47
Pad and fan cooling greenhouses	United Arab Emirates (the) (Closed substrate culture)	48
Climatic controlled soilless greenhouses	France (Open system)	39
	Netherlands (the) (Closed system)	66

Source: *Nederhoff and Stanghellini, 2010.*

Lorenzo *et al.* (2006) found that shading greenhouses improved the quality of tomatoes and increased cucumber yields. It also reduced crop transpiration and, thus, water uptake and improved water use efficiency by 47 percent and 62 percent, respectively, for tomato and cucumber crops. Crops grown in open field in a semi-dry climate are subjected to direct sunlight, high temperatures and wind, resulting in high crop evapotranspiration. These crops require large amounts of water. In contrast, shade-houses favour plant growth as plants are less stressed, direct sunlight is avoided, humidity is higher and wind speed is reduced. Irrigation water requirements have been estimated at 23 to 31 percent of pan evaporation for plants grown under 70 percent light reduction (shading). Also, water use efficiency increased under shady conditions (Jifon and Syvertsen, 2003).

The actual water consumption throughout the crop cycle of several vegetable crops grown in the Jordan Valley in non-cooled plastic greenhouses was measured using the soil depletion method (Mazahrih *et al.*, 2001, 2003, 2004). The findings showed that tomatoes consumed 356 mm, cucumbers consumed 214 mm, beans consumed 159 mm, and peppers consumed 271 mm. Moreover, it was determined that peppers grown in greenhouses consume

47 percent the amount of water consumed by peppers grown in the open field (Mazahrih *et al.*, 2004). The same authors found that alfalfa consumed 40 percent less water under greenhouse production than under open-field production. The water productivity of tomatoes and cucumbers was measured at 39.7 and 62.4 kg/m^3, respectively, and net profit revenue per cubic meter of water for beans and peppers was calculated at USD 12.85 and USD 3.7 respectively.

Soilless techniques can increase water-use efficiency and improve water and fertilizer management in crop production. A good grower might achieve the same yield in the soil as in a closed soilless production system but is likely to use 50 to 100 percent more water. The success of soilless production systems depends on the type of substrate used, the water and nutrient management system, and cooling and ventilation requirements. Soilless production systems can be classified into two major types:

- Open system soilless culture, with manual or automatic water and nutrient provision. In this system, the nutrient solution supplied to the root zone is not recycled.
- Closed system soilless culture, with manual or automatic water and nutrient provision. In this system, the nutrient solution supplied to the plant root zone is recovered, replenished and recycled.

The National Center for Agricultural and Research Extension (NCARE) in Jordan conducted field observations to determine water, fertilizer and pesticide consumption and yield in different cultivation systems. A simple comparison was made between the amount of water used in greenhouse production using sandy soil vs. that of soilless culture in greenhouses, using tuff as a substrate. The results showed great success in saving water in soilless greenhouse production. Pepper plants grown in tuff in greenhouses consumed over 40 percent less water than those grown in soil in conventional greenhouses. This success in water savings extends to many other crops, including cucumbers, peppers and medicinal and aromatic plants.

Moreover, during field observations, farmers reported the following benefits when growing several crops using fine volcanic rock (tuff) as a growing medium in automatic closed production systems in which the application of irrigation water and fertilizers could be controlled:

- over 40 percent increase in production with excellent fruit quality;
- early production and longer growing season (cucumber produced 21 days after planting);
- water savings of up to 35 percent;
- fertilizer savings of around 50 percent;
- less farm labour required;
- pesticide savings of 50 percent.

CHAPTER 2
OVERVIEW OF AGRICULTURE IN THE GULF COOPERATION COUNCIL COUNTRIES

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CHAPTER 2

OVERVIEW OF AGRICULTURE IN THE GULF COOPERATION COUNCIL COUNTRIES

2.1 INTRODUCTION TO AGRICULTURE IN THE GULF COOPERATION COUNCIL COUNTRIES

2.1.1 NATURAL RESOURCES

The GCC countries face multiple environmental challenges, including desertification, loss of biodiversity, pollution in marine and coastal areas, air pollution, water scarcity and the deterioration of water quality. The economic costs of environmental degradation in the Arab region are real, substantial and growing. Natural resources are being used unsustainably, undermining economic development and poverty reduction efforts. The World Bank estimates that the annual cost of environmental degradation amounts to between four and nine percent of GDP in certain Arab countries (Croitoru and Saaraf, 2010).

FOOD PRODUCTION CONSTRAINTS

The limited land and water resources in the GCC countries pose a substantial technological challenge to increasing domestic food production (Shah, 2010). Of the region's total land area of approximately 267 million ha, only 1.8 percent is currently under cultivation, mainly using groundwater irrigation. The total irrigated area is equal to 1.4 million ha. Although about one-fifth of the total land area is potentially cultivable, the region's arid climate and constraints caused by severe biotic and abiotic stresses, including heat, salinity and lack of improved cultivars, limit the potential levels of food sufficiency that can be achieved.

LACK OF RENEWABLE WATER

According to Al-Rashed and Sherif (2000), one critical problem that hinders sustainable development in the GCC countries is the lack of renewable water resources. Rainfall in the Arabian Peninsula is meagre and infrequent. Over-exploitation of fossil groundwater resources, mostly to meet the irrigation demands and create greenery lands, has already affected the productivity of the region's aquifers, both quantitatively and qualitatively.

LIMITATIONS IN AGRICULTURE / FOOD SECURITY

The combination of water scarcity, declining arable land, poor soils, a hyper-arid environment and projected climate change impacts in the GCC countries constrains agricultural production in the region and the capacity of the countries to meet the food demands of their current and future populations from local production. This raises serious concerns about food security in food insecure but capital rich countries. Thus, boosting food self-sufficiency has emerged as a goal in the GCC countries. An important advantage in this regard is that the GCC countries are endowed with abundant solar radiation which could be used as a renewable energy source for sustainable protected agriculture, waste water treatment and desalination (Alnaser and Alnaser 2011; El Katiri and Husain 2014).

INCREASED DEMAND OF WATER FOR AGRICULTURE AND POPULATION GROWTH

Demand for water in the GCC states has risen by a massive 140 percent since the mid-2000s. Kuwait tops the list with its increased demand for municipal water. Significant change in the distribution of water allocations in the six member states is unlikely in the near future, but the aggregate allocation for the agricultural sector in the GCC countries is expected to drop from an average of 63 percent in 1995 to 48 percent by 2025 (Wallace, 2000). Meanwhile, the combined population of all six states has quintupled over the past few decades, increasing from around eight million people in the 1970s to some 43.5 million in 2010 – one of the highest population growth rates in the world (Grey and Sadoff, 2007). Since the 1980s, accelerating development and population growth have increased water demand dramatically from 6 billion m^3 in 1980 to more than 32 billion m^3 in 2005 (Fathollahzadeh, 2008). It is clear that increased demand for water results from three interconnected factors: population growth, agriculture and industrial development, aggravated by excessive water consumption patterns.

AGRICULTURAL SECTOR: LARGEST WATER CONSUMER

Sharp increases in population and the ensuing rise in the demand for food, led most GCC countries to devise ambitious agricultural policies which aim to sustain social and economic development and achieve higher levels of food self-sufficiency. As a result, the agricultural sector has become the region's largest consumer of water, accounting for more than 85 percent of gross water usage in these countries (Fagan, 2011).

LACK OF RENEWABLE WATER AND POSSIBLE OPTIONS

The dilemma for the Arab region is that it is among the most water-scarce regions in the world. The average annual available water per capita in the GCC countries was less than 500 m^3 in 2001, falling below the United Nations' definition of water scarcity. Moreover, projections are bleak: by 2023, the figure is expected to decrease to 360 m^3 per capita. All GCC countries are projected to experience severe water stress by 2025 (Tolba and Saab, 2008).

Combining renewable energy, such as solar energy, with desalination could be a key solution to decreasing greenhouse gas emissions and reducing energy bills (Kalogirou, 2005). Unconventional water resources, such as treated wastewater and saline water, could be utilized for a variety of purposes in agriculture, landscape irrigation, groundwater recharge, industrial cooling, forest irrigation, etc. These would be win-win solutions, preserving the environment (especially coastal ecosystems) from pollution due to wastewater disposal while providing additional water resources other than fresh water, which could be used for drinking (Choukr-Allah, 2012).

WATER AVAILABLE BY COUNTRY

Table 2.1 shows the precipitation and renewable water resources of the GCC countries. Renewable water resources are in linear correlation with the area of each country. Perennial rivers and lakes do not exist in any of the countries. Surface water resources are scarce to absent, with the exception of the mountainous areas in south-western Saudi Arabia, the southern part of United Arab Emirates (the) and the northern and southern parts of Oman.

Table 2.1 Precipitation and renewable water resources of the Gulf Cooperation Council countries

Country	Precipitation (mm)	Renewable water resources (10^6 m^3)	Area (1 000 ha)
Saudi Arabia	59	2 400	214 969
United Arab Emirates	78	150	8 360
Qatar	47	56	1 161
Kuwait	121	5	1 782
Oman	125	1 400	30 950
Bahrain	83	4	76

Source: *FAO, 2017.*

DESALINATION OF WATER BY COUNTRY

Kuwait, Saudi Arabia and United Arab Emirates (the) are considered the largest users of desalinated water in the region. Seventy-seven percent of the all the desalinated water used in the region is used in these three countries. Table 2.2 shows the capacity of the desalination plants in the GCC countries.

Table 2.2 Desalination capacity and production in the Gulf Cooperation Council countries

Country	No. of plants	Capacity (Mm^3)	Production (Mm^3)	Capacity (Mm^3/day)	Production Mm^3/day
Bahrain	3	138	122	0.38	0.34
Kuwait	6	525	478	1.44	1.31
Oman	2	103	67	0.28	0.19
Qatar	2	178	158	0.49	0.43
Saudi Arabia	23	1 278	1 063	3.50	2.91
United Arab Emirates	8	952	812	2.61	2.23
Total	44	3 174	2 702	8.69	7.40

Source: *Bazza, 2005.*

TREATED WASTEWATER IN THE GULF COOPERATION COUNCIL

Wastewater reuse in water-stressed countries holds the potential to reduce water scarcity and expand the irrigated area for food production. However, unless wastewater is appropriately treated, its use in agriculture poses serious risks to public health and the environment.

Treated wastewater is increasingly becoming a source of water for use in agriculture worldwide (World Bank, 2010). Treated wastewater is a non-conventional water resource which can replace freshwater for many purposes, including irrigation, artificial recharge of groundwater and industrial cooling. The six GCC countries use 1.4 million m^3 of treated wastewater per day for agriculture (World Bank, 2010). That amounts to 511 million m^3 per year, which constitutes almost 37.3 percent of the total treated wastewater of about 1 370 million m^3 per year (FAO, 2013). The remaining wastewater is discharged without treatment. The GCC countries employ a higher percentage of treated wastewater in agriculture than other Arab countries because of their severe scarcity of freshwater resources. The GCC countries have also adopted improved wastewater treatment standards to ensure its safety. Table 2.3 shows the total withdrawal, wastewater produced and volume of treated wastewater in the GCC countries. The volume of treated wastewater produced by the countries indicates the great potential in reusing treated wastewater. Due to its large population, Saudi Arabia produces the greatest volume of treated wastewater. However, Kuwait is the most efficient country in terms of wastewater treatment, treating 28 percent of the water withdrawn.

TREATED WASTEWATER IN UNITED ARAB EMIRATES (THE) AND COMBINING SOLUTIONS

In United Arab Emirates (the), due to shortages in conventional resources, the production of treated water is increasing 10 percent annually. This type of water can be utilised for domestic purposes after ensuring it is suitable for such use (Al-Dabbagh, 2015). The number of wastewater treatment plants have also increased. There are 19 plants in Abu Dhabi Emirate, with a total annual capacity of 884 million m^3. Dubai Municipality produced 72 million m^3 of treated water in 2000, increasing to 142 million m^3 in 2006 – an increase of 97.4 percent. In Sharjah Emirate, there are seven wastewater treatment plants, with a total capacity of 0.16 million m^3 per day. The total production of treated water from all seven stations in Sharjah was 0.15 million m^3 per day in 2006 (Ahmed, 2010).

Table 2.3 Total withdrawal, wastewater and volume of treated wastewater in the Gulf Cooperation Council countries

Country	Total water withdrawal (10^6 m^3/year)	Total wastewater produced (10^6 m^3/year)	Volume of treated water used (10^6 m^3/year)
Bahrain	357	191	96
Kuwait	913	292	219
Oman	1 321	90	37
Qatar	444	274	118
Saudi Arabia	23 666	1 546	1 067
United Arab Emirates	3 998	500	290

Source: *Aleisa and Al-Zubari, 2017.*

ALTERNATIVE ENERGY SOURCES

There is significant technological expertise in the region in renewable energy technologies (such as solar energy). Solar applications, especially photovoltaic, are regarded as the best and least expensive means of providing the basic energy services. However, the solar energy applications are still largely underused in the region.

WATER POLICY/GOVERNANCE

A water policy is the framework by which available water resources are managed, and the set of rules and regulations governing water management internally and externally. National water security policies are water policies adopted at a national level by each state within the GCC. From the perspective of integrated water-resources management (IWRM), most reports concerning global water issues indicate that three kinds of problems need to be addressed, namely:

- problems caused by extreme waste of water resources;
- problems that are well known and for which no economically efficient solution is available at this time;
- problems resulting from excessive demand for water, which are now being studied and analysed through governmental policymaking and investment strategies (IPS News Agency, 2010).

A study by the Organisation for Economic Co-operation Development (OECD, 2001) indicates that the two main factors preventing better water governance in the OECD countries are the multiplicity of government institutions responsible for water resources and generally poor governance at all levels. Improving water governance at all levels is key to the sustainable management of water resources and essential for achieving water security.

National water security policies – those already adopted and those that might be adopted in the future – can be divided into supply-based and demand-based policies. In terms of demand-based policies, researchers have been working hard to determine the optimal instruments and mechanisms for water-demand management. These include analysing modern irrigation techniques, the privatisation of the water industry, government subsidisation of water in urban areas, and water quota systems.

Comprehensive reviews of the distribution of water to various sectors, and public water-awareness campaigns derived from the World Bank's new thinking on water management are contributing to transforming the more traditional supply-side management approach with strategies focusing instead on managing demand (Al Farra, 2015).

Demand-management measures include:

- using modern irrigation technologies and saline water for irrigation where possible;
- developing strains of crops that require less water and modifying crop mixes;
- redistributing water supplies among other sectors;
- rationalising water consumption and promoting water awareness (Al-Farra, 2015).

2.1.2 AGRICULTURAL ACTIVITY AND FOOD SECURITY

Government initiatives in the GCC countries have focused on ensuring food security through various means. The ongoing trend to invest in local food producers and manufacturers has made it possible to integrate the latest technologies, helping to partially offset reliance on food imports and keeping in line with food security strategies for the region. These government initiatives also aim to allow local players to develop strong brands at home, while working to become international brands and compete on the food export market. Agriculture does not represent a significant component of the GCC economies as an exceptionally arid climate and low capital investments have limited its contribution to GDP and employment. Presently, agriculture accounts for only 1.4 percent of the GDP of the GCC countries, significantly lower than the 10 to 15 percent contribution of the sector in relatively more water-rich Middle Eastern nations, such as Egypt and Turkey, and much lower than the 15 to 20 percent the sector contributes in India and China. In terms of employment, the sector is most important in Oman and Saudi Arabia, but is of negligible importance elsewhere in the region. (This is due to lower levels of urbanization in Oman and Saudi Arabia and a more aggressive regulatory push to develop the sector. Thirty-five percent of the economically active population in Oman, and 9 percent in Saudi Arabia, is employed in agriculture.

Figure 2.1 shows the agricultural GDP in the GCC countries. Data indicate that Saudi Arabia's agricultural GDP is the highest in the region, representing 75 percent of the total agricultural GDP in the GCC, followed by Kuwait and Oman. However, the total agricultural GDP of the GCC represents only 1.4 percent of the GCC's overall GDP.

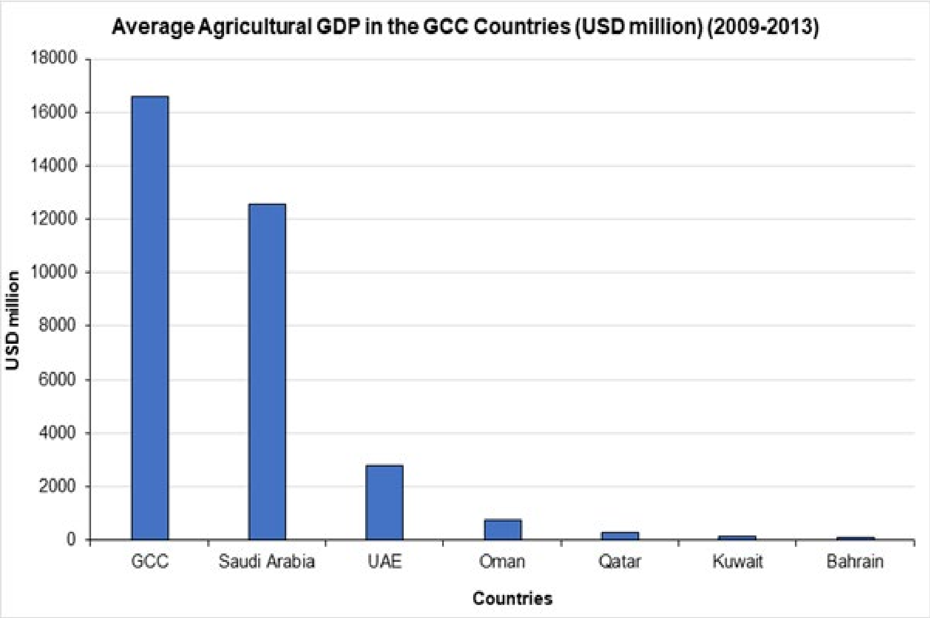

Figure 2.1 Average agricultural GDP in the Gulf Cooperation Council countries (USD million) (2009-2013).

Source: *FAOSTAT, 2011.*

According to Kotilaine (2010), the demand for all food products has seen robust growth in the GCC. Total consumption of food products (crops, vegetables, meat, eggs, fish, fruits, sugar, oil, poultry and dairy) grew from an average of 28.9 million metric tons during the period 1999 to 2003 to 38.0 million tons in 2007. The consumption of cereals and pulses grew from an average of 12.4 million tons for the period 1999 to 2003, to 17.4 million tons in 2007 (46 percent of total GCC food consumption that year). Consumption of animal products (meat, fish, eggs and dairy) reached 8.2 million tons in 2007 (21 percent of total consumption), up from an average 6.4 million tons during the period 1999 to 2003. Beyond the broader trends, however, dietary patterns vary a great deal across the Gulf region, as indicated below:

- Cereals account for 52 percent of total food consumption in Saudi Arabia, which is the largest consumer of agricultural produce in the region, accounting for 66 percent of total GCC food consumption and three-quarters of cereal consumption (2007).
- Within cereals, the Saudis tend to prefer barley, which regionally accounts for 46 percent of total cereal consumption, followed by a 25 percent share for wheat and flour. However, barley is not popular outside of Saudi Arabia, having a share of only 9 percent in the rest of the region where wheat and rice dominate, at 38 percent and 28 percent, respectively.
- Vegetables and fruits are the largest component of food consumption in United Arab Emirates (the), accounting for 35 percent.
- Bahrainis consume the least amount of cereals in the region. Cereals account for 15 percent of their diet, compared to animal products, which account for 41 percent. Kuwait and Qatar also rely rather heavily on animal products (36 percent and 39 percent, respectively).

Table 2.4 shows the cropping pattern of cultivated crops in the GCC countries. Data indicate that the palm tree is the dominant crop for all GCC countries, followed by vegetables. Oman, for example, has more than 1.18 million ha of cultivated crops, and half of this area is dedicated to vegetables.

Table 2.4 Cropping area in the Gulf Cooperation Council countries (ha)

Crops	Bahrain	Kuwait	Oman	Qatar	Saudi Arabia	United Arab Emirates
Palm trees	3 195	8 931	36 255	2 290	107 281	28 485
Vegetables	262	4 332	1 072 400	1 782	79 426	6 422
Fruits	413	363	5 977	101	14 872	1 606
Cereals	0	2 454	69 287	326	236 026	1 848
Pulses	13	0	0	0	4 932	0
Others	0	44	299	0	3 098	42

Source: *FAOSTAT database. Crop data. http://www.fao.org/faostat/en/#data/QC.*

The GCC countries import at least 50 percent of the food calories they consume. As the largest net importers of cereal, Arab countries are more exposed than other countries to severe swings in agricultural commodity prices and their vulnerability will probably be exacerbated in the coming years by strong population growth, low agricultural productivity and their dependence on the global commodities markets. Projections of the region's food balance indicate that dependence on imports will increase by almost 64 percent over the next twenty years.

According to FAOSTAT (2011), the value of food imports in the GCC countries was about USD 23 billion in 2011, with Saudi Arabia alone importing about half of the total GCC food imports due to its large population (Figure 2.2).

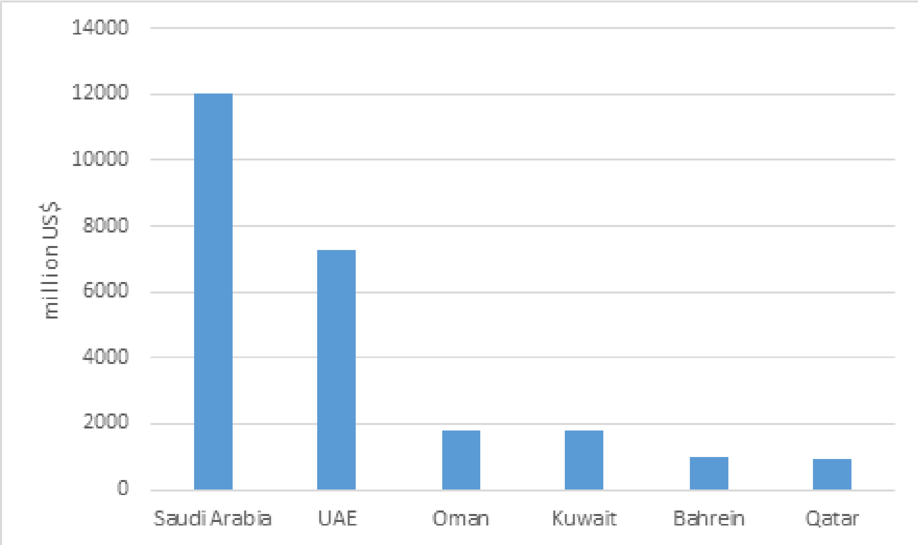

Figure 2.2 Food imports of the Gulf Cooperation Council countries

Source: *FAOSTAT, 2011.*

As shown in Table 2.5, the GCC countries import most of their agricultural food needs and 100 percent of their rice and barley needs. As to wheat, all GCC countries import their wheat requirements except Saudi Arabia, which nearly meets its demand for wheat internally. Qatar (83 percent) and United Arab Emirates (the) (79 percent) are both highly dependent on external food supplies, while Saudi Arabia is less dependent (50 percent).

Table 2.5 Food imports as a proportion of consumption in 2007 (%)

Imported food	Bahrain	Kuwait	Oman	Qatar	Saudi Arabia	United Arab Emirates	GCC
Wheat and flour	100	99	99	100	2	100	39
Maize	100	92	100	93	91	100	92
Rice	100	100	100	100	100	100	100
Barley	100	96	92	98	100	100	100
Potatoes	100	17	76	100	-2	91	19
Pulses	100	100	100	100	100	89	98
Vegetables	78	41	36	86	22	62	37
Fruits	77	73	23	77	35	47	40

Table 2.5 (continued)

Imported food	Bahrain	Kuwait	Oman	Qatar	Saudi Arabia	United Arab Emirates	GCC
Meat	62	62	73	89	44	80	56
Fish	-51	64	-74	36	40	29	16
Eggs	43	37	53	63	-4	62	19
Milk & dairy products	91	92	64	93	72	83	77

Source: *Kotilaine, 2010.*

Table 2.6 presents the food gap value (FGV) in the GCC countries and shows their agricultural deficit and dependency on external food supplies. Saudi Arabia accounts for 44 percent of the GCC's total FGV, while Oman is less dependent on foreign markets for its food.

Table 2.6 Values of the food gap in the Gulf Cooperation Council countries.

Country	Food gap (USD billions)	Rate (%)
Bahrain	0.4	2.1
Kuwait	1.4	7.5
Oman	0.7	3.6
Qatar	1.3	6.6
Saudi Arabia	8.6	43.9
United Arab Emirates	7.2	36.7
Total	19.6	100

Source: *Alpen Capital, 2013.*

2.2 PROTECTED AGRICULTURE IN THE GCC COUNTRIES

The GCC countries are considered one of the most water scarce regions in the world, and will be facing the most severe intensification of water scarcity in history over the coming years. Agriculture plays an important socio-cultural role (heritage) and is key to food security, and it is the sector using by far the majority of available fresh water resources (>85 percent, of which 92 percent is used for dates and forage production) (Kotilaine, 2010). As such, agriculture is the prime target for water conservation efforts, and improving water management, performance and productivity in major agricultural systems is a major issue within the strategy of most Gulf countries. Protected agriculture can offer problem-solving approaches to challenges involving water and food supplies. Soilless culture is one of the spearheads in the process of successful expansion of protected agriculture (Wittwer and Castilla 1995).

In 1988, ICARDA established the Arabian Peninsula Regional Program (APRP), aiming to develop the agriculture sector and conserve natural resources and the environment through scientific research and technology development. This was achieved through various research and training projects carried out in close collaboration with national agricultural research and extension systems (NARES) in the Arabian Peninsula countries (Bahrain, Kuwait, Oman, Qatar, Saudi Arabia, United Arab Emirates [the] and Yemen.

The joint efforts of ICARDA and the NARES in the countries of the Arabian Peninsula resulted in six recommended technology packages that address the major constraints to increasing water use efficiency in the production of high-quality cash crops and irrigated forages.

Although protected agriculture improves water productivity, access to water of satisfactory quality in an environment as harsh as the Arabian Peninsula is still a big concern. In addition to water scarcity, productivity in greenhouses is dropping due to the accumulation of salt and pathogens in the soil. To tackle this, ICARDA-APRP collaborated with the NARES in seven countries to develop a simplified protected hydroponics system that would be manageable for the growers and allow them to produce high-quality cash crops without soil and using significantly less water. Various soilless systems for different crops, including cucumber, tomato, pepper, muskmelon and strawberries, were tested in research stations, and those that proved successful are being transferred to growers with the systems that were developed, water productivity increased up to eightfold along with a significant improvement in yield (ICARDA - APRP, 2013).

In the context of this programme, member countries carried out a number of activities that led to the consolidation and further development of protected agriculture in each country, particularly in the following areas:

- upgrading and developing greenhouse design, structure, size, cover and ventilation;
- evaluating cooling system efficiency;
- adopting improved cultivation systems and practices in relation to land and water use efficiency, fertigation and post-harvest technology;
- using IPPM technology and tools.

Annex 1 provides a summary of the status of protected agriculture in the six GCC countries.

2.3 THE POTENTIAL OF PROTECTED AGRICULTURE TO IMPROVE AGRICULTURAL PRODUCTION IN THE GULF COOPERATION COUNCIL COUNTRIES

The drylands of the world, including the GCC countries, suffer from a significant increase in temperature and severe water scarcity, which affect agricultural production. Therefore, the GCC countries have adopted protected agriculture to provide a relatively suitable environment for plant growth, to increase productivity per unit area and to improve water-productivity, compared to open-field agriculture. Because of these advantages, most of the GCC governments have scaled-up this technology through programs that support protected agriculture, including awareness campaigns. The governments' efforts to disseminate the technology have had a positive impact. The number of farmers who have built greenhouses at their own expense is greater than those who received support. However, farmers very often encounter limitations that hinder their adoption of modern technologies.

Currently, there are almost 13 000 ha of protected agriculture in the GCC. However, due to the high temperatures, the greenhouses are cooled and thus consume large amounts of energy and water. In fact, greenhouse energy consumption is the largest component of the system's environmental impact, especially during the hot season, from May to September. This is true of any greenhouse production system in any hot climate. In the Mediterranean region, for example, greenhouse production consumes around 100 000 kWh/ha per year - a high energy cost. In the GCC, where summer temperatures are much higher than those of the Mediterranean, it can be inferred that greenhouse cooling consumes a great deal more energy. Thus, the goal of reducing energy consumption and increasing the use of energy from sustainable sources is of great importance for greenhouse growers.

In 2010, total crop production in the GCC countries in open fields was 2.1 million tons, 74 percent comprising forages and field crops. Fruit trees contributed 19 percent, while vegetables accounted for only 7 percent. The situation of protected agriculture changed significantly in 2011 when total production fell to 1.2 million tons. This drop may have been due to problems with salinity and water scarcity, illustrating the need for better saline water management and increased saving of fresh water.

Energy and water, our two most precious sources of life and prosperity, are highly interdependent. Large amounts of water are necessary to produce energy. (Although the oil and gas industry does not necessarily require fresh water.) Likewise, large amounts of energy are necessary to produce fresh and clean water. This interrelationship has become ever more important as the world's demand for energy and water surges and as our livelihoods depend increasingly on these resources. It should be noted that cooling a greenhouse can be achieved with or without evaporating water with or without evaporating water, although dry cooling (without evaporating water) uses more electricity for the same amount of cooling than using evaporating water to cool the greenhouse.

The GCC countries are the highest energy consumers per capita in the world. Consequently, environmental pollution and emissions have been a major challenge facing these countries over the past several years, particularly due to unprecedented economic growth and high population increase. A key measure that the GCC countries could take would be to increase the use of renewable energy in order to achieve sustainable development without major environmental consequences.

The scarcity of fresh water, due to limited groundwater resources and the salinity of most aquifers, is another major challenge for the GCC countries. Desalination provides the bulk of fresh water mainly for drinking water and, recently, for irrigation as well. Combining renewable energy, such as solar energy with desalination, could be a key solution in facing the energy and water requirements for protected agriculture while complying with the need to reduce greenhouses gas emissions and strengthen climate change resilience.

Since oil and gas resources will not

last forever, the development of clean and renewable energy seems to be the judicious solution to achieve sustainable development.

2.4 CONSTRAINTS AND OPPORTUNITIES FOR GREENHOUSE PRODUCTION SYSTEMS IN THE GCC COUNTRIES

2.4.1 CONSTRAINTS FOR PROTECTED AGRICULTURE PRODUCTION IN THE GULF COOPERATION COUNCIL COUNTRIES

Weather conditions and water salinity

The extended period of high summer temperatures, low rainfall, high evaporation rates and sand and dust storms create problems in greenhouse operation and increase production costs. Furthermore, heavy storms can destroy the plastic covering of greenhouses, which may lead to loss of the crops before the end of the season. Increasing water salinity is another major challenge facing not only protected agriculture but the entire agricultural sector in the GCC.

HIGH INITIAL COST

The cost of greenhouse production is high compared to that of open-field production because of the high initial capital investment required. Greenhouses have high production costs, face stiff competition from imported commodities and the payback period after initiating greenhouse production is longer than it is for many other investments. Moreover, the price of hybrid seed is very high, and farmers have difficulties selecting good cultivars owing to the absence of cultivar screening and evaluations as hybrid cultivars are not produced locally.

LACK OF EFFICIENT AND ECONOMICAL COOLING SYSTEMS

The use of brackish water presents problems in evaporative cooling systems due to the encrustation of cooling pads. Irrigation with highly saline water in soil-based greenhouse cropping systems imposes physiological stress on the plants and increases soil salinity. To overcome this problem, growers use desalinated water for greenhouse cooling and irrigation, but the use of desalinated water for cooling is not economical, requiring more water per plant than is needed for irrigation. Thus, cooling systems must be improved in order to increase water use efficiency.

SANDY SOILS WITH LOW CATION EXCHANGE CAPACITY, WATER-HOLDING CAPACITY AND FERTILITY

Natural fertile land is a scarce resource in the GCC countries. Most of the area is desert land that is predominantly sandy with low organic matter content, low water-holding and cation exchange capacity. Soil salinity and salinisation is a problem predominantly in the coastal areas where the climate for agriculture is more favourable.

Adoption of soilless production systems could eliminate most of the problems associated with soil-based farming, such as expensive soil sterilisation and the application of hazardous agrochemicals in conventional greenhouses. Soilless production can provide optimal conditions for plant growth and therefore, higher yields, compared to conventional soil-based agriculture. Soilless production also improves water-use efficiency and offers opportunities for better water and fertiliser management.

PESTS AND DISEASES

The greenhouse environment is generally warm and humid, with low air velocities. This ideal for plants, but is also an excellent condition for pests and diseases. Farmers use chemicals to mitigate this problem, but their lack of experience in using chemicals in protected agriculture leads to several problems, such as residual effects on human, plant and environmental health. The extensive use of chemicals to control diseases and pests also results in complicated problems of increasing resistance to such chemicals (Moustafa *et al.*, 1998).

INADEQUATE TECHNICAL KNOWLEDGE AND MANAGEMENT PRACTICES

Greenhouse production requires skills and technical expertise to ensure effective and efficient operation. There is a shortage of trained personnel even within research and development cadres and more so among growers, workers and national extension staff. Consequently, very few extension and training programmes are available for growers. There is also a generalized lack of technical supervision in protected agriculture, lack of baseline information regarding water and fertilizer requirements, and insufficient scientific research and extension recommendations regarding cultivars, water-use efficiency, optimum water requirement and fertigation. Furthermore, growers do not invest enough time and money in training and knowledge development and are also not used to paying for technical support from experts in plant nutrition, pest and disease control, planning and marketing.

Profitability in protected agriculture is largely determined by the choice of the crop (cultivar) and the level of technology used. Technical support for protected agriculture, especially regarding crop diversification, new technologies and their adoption, remains limited in GCC. At present, only a narrow range of crops is grown in protected agriculture, primarily cucumber and tomatoes, (Tomato under protected agriculture is less profitable than cucumber.) Neither of these crops can be grown in summer months without cooling. While information from suppliers regarding cultivars and other aspects of greenhouse production is useful, it is essential that producers have unrestricted access to unbiased technical information.

There are many needs for training in protected agriculture that require qualified and experienced personnel. The development of low-cost and high-efficiency types of greenhouses suitable to this area is also very important. Additionally, smallholders require support to find the right way to maximize their income and to improve efficiency.

INADEQUATE MARKETING

The most important reason for using protected agriculture is to modify the traditional harvest dates of crops to provide a broader range of products in response to sustained consumer demand increases. A disadvantage of protected agriculture is its relatively high cost. As such, growers must have distinct marketing opportunities to cover this cost. The efficiency of marketing performance determines the amount of income and return on the investment and the advantage or disadvantage of continuing with this type of production. A limiting factor in this regard is that GCC producers face high competition from produce imported from other countries in the region and market intelligence is not available to them.

2.4.2 PROSPECTS FOR CONSOLIDATING PROTECTED AGRICULTURE

CONTINUOUS MODERNIZATION OF TECHNOLOGIES

Climate conditions, available natural resources and social structure are very similar throughout the Arabian Peninsula. As a result, the challenges of protected agriculture (the type of structure, cover materials, irrigation and fertigation, production forecasting, pests and diseases and marketing) are similar across the region. Networking is an efficient and economical way to share and exchange available information and experiences to tackle problems of common interest (Moustafa *et al.*, 1998).

Protected agriculture is expected to become an important agribusiness with greater impact on the national economies than was initially perceived. Therefore, the revived greenhouse sector in the GCC, if managed properly, will have enormous opportunities for optimizing the production of selected commodities. Water-use efficiency in crop production is also expected to improve considerably. The production system will have to be made both efficient and productive to achieve this goal, which is possible only through the development and demonstration of water- and energy-efficient technology packages and the infusion of high-quality managerial skills.

The first step towards modernizing protected agriculture in the GCC is to evaluate and incorporate all the proven technologies of greenhouse management, fertigation, water application and pest and disease control into the existing operations. For example, providing uncooled greenhouses with efficient cooling systems would reduce water consumption, extend the harvest period, offer opportunities for crop diversification and automation, and increase productivity; resulting in higher price realization and, ultimately, increased self-sufficiency. More research on multi-span greenhouses and modifications in cooling systems to allow the use of brackish water will also be required to determine their feasibility in the GCC countries.

ENHANCEMENT OF COOPERATION AMONG NATIONAL AND INTERNATIONAL RESEARCH CENTRES IN THE GULF COOPERATION COUNCIL

The existence of national and international research and development support agencies such as FAO, ICARDA and ICBA, and their continued cooperation, is one of the most important opportunities to overcome the obstacles of protected agriculture expansion in the GCC. Coordination between the GCC countries is also necessary in order to identify international organizations and institutions that can support the development and sustainability of rural development programmes in the region.

ICARDA is the first research organization to develop a regional research programme for protected agriculture as part of its wider Arabian Peninsula Regional Program (APRP). Among other actions, ICARDA organized the International Workshop on Protected Agriculture for the Arabian Peninsula to identify the problems, constraints and research and development priorities of protected agriculture. This workshop contributed to developing a strategy to achieve specific goals in the development of protected agriculture in the region. Finally, networking and knowledge sharing across national research and development teams and pilot farmers, as well as training, took place at the annual APRP project meeting, strengthening the region's social capital, building confidence and promoting the pooling of resources to address common research problems.

Another research center in the region is the Agricultural Innovation Center (AIC), established at the Al-Dhaid agriculture research station, in United Arab Emirates (the). Currently, the country's agriculture sector uses over 75 percent of the available national water resources, and this significant amount has an enormous cost for the environment and overall development sustainability in the Arabian Peninsula.

It is accepted that partial switching from open-field production to protected agriculture will save a significant amount of water, which can then be used for other purposes. This approach will offset considerably the constraints of limited farmland and water scarcity. To establish the Al-Dhaid AIC, the Ministry of Climate Change and Environment (MCCE) liaised with international organizations operating in United Arab Emirates (the), such as the ICBA, FAO and ICARDA.

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CHAPTER 3
GREENHOUSES: THE ULTIMATE PROTECTED AGRICULTURE SYSTEM

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CHAPTER 3

GREENHOUSES: THE ULTIMATE PROTECTED AGRICULTURE SYSTEM

3.1 OVERVIEW OF CURRENT GREENHOUSE TECHNOLOGIES AND CULTIVATION

Over the ages, growers have developed ways of altering the environmental conditions for their crops in order to hasten production and improve the quality of their produce. A wide range of controlled environments is possible, from the simple choice of a sunny exposure, sheltered from the wind, to the manufacture of fully air-conditioned units, possibly equipped with artificial lighting. The choice of controlled environments is limited by the level of capital investment and operating costs that the user is prepared to bear and by the cost-effectiveness based on related market prices for the produce.

There are different ways to protect plants from unsuitable environmental conditions. They are described in this section.

3.1.1 PROTECTIVE MEASURES

WINDBREAKS

Even where winds are neither violent nor frequent, windbreaks decrease the average level of turbulence quite significantly, thereby favouring the production of quality crops by limiting mechanical damage and early crop maturity due to a slight increase in the average air temperature (about 1 ºC).

However, any reduction in turbulence increases the diurnal variation of temperature. Consequently, in periods of frost, the risks of damage are aggravated since the minimum temperatures are reduced up to 1 to 2 °C at ground level. (See Figure 3.1.)

Figure 3.1 Windbreaks

Source: *El-Behairy, 2015.*

MULCHING

Plastic mulching is used for various purposes: microclimatic modifications near the ground, weed control or to keep plants off the ground due to phytosanitary concerns. Mulching increases ground temperatures by 1 to 50 °C, according to the nature of the film and how it is placed. On the other hand, mulching hardly affects air temperatures, even at ground level. (Figure 3.2.)

Figure 3.2 Plastic mulching

Source: *El-Behairy, 2015.*

LOW TUNNELS

Semi-forcing tunnels are used for short periods in order to help crops grow faster when temperatures are too low. Furthermore, they are often associated with mulching. The cumulative effects of these two techniques raise ground and air temperatures by 5 to 10 ºC during the daytime. As soon as solar radiation intensifies, the air temperature under the tunnel becomes excessive, and ventilation becomes necessary. This can be achieved through perforations or by rolling up the film. In contrast, during the night, the temperature undergoes relatively slight changes (Figure 3.3).

Figure 3.3 Low tunnels

Source: *El-Behairy, 2015.*

3.1.2 STRUCTURES FOR PROTECTED CULTIVATION

Structures for protected cultivation must provide optimal climate conditions for the growth of the plants. They must protect plants against excessively low and high temperatures, wind, rain, hail, birds and insects (Waaijenberg, 2006). The following components are very important for the successful design of such structures: shape, orientation, structure, cladding material, foundation, ventilation and technical equipment for climate control.

Structures for protected cultivation can be classified into greenhouses and net or shade houses, the latter being used mostly in tropical regions.

SHADE AND NETHOUSES

Shade and nethouses have water-permeable cladding nets, which shade the plants and protect them from incoming insects, as long as they completely cover the roof and sidewalls, and the mesh is small enough (Figure 3.4). They reduce excessive radiation, wind speed and the impact of heavy rain; but they do not block precipitation from reaching the plants. In nethouses moderate precipitation will clean accumulated dust from the nets and may have a positive effect on leaching fertilizers in excess of plant requirements. It is possible to monitor fertigation systems under nethouses even in the rainfall pattern prevailing in the GCC region. Shade or nethouses have a positive effect on water-use efficiency.

Figure 3.4 Shade house

Source: *El-Behairy, 2015.*

GREENHOUSES

Greenhouses have cladding material that is impermeable to water and has a high natural light transmittance. Greenhouses protect the crops from rain and other climate factors. Usually, the cladding material is a plastic film in mild climates and glass or rigid plastic in temperate and cold climates (Von Zabeltitz, 2011). (See figures 3.5 and 3.6.)

The width of one span depends on the available width of the plastic film if the roof is covered by the film in a longitudinal direction, which is the recommended approach. The width of the available cladding material is limited in many countries by the manufacturing process. The shape of the construction, the height of the eave and ridge (the entire volume), the cladding material, and the number of spans influence internal climate conditions such as temperature, humidity, light transmittance, and CO_2 buffer (Von Zabeltitz, 2011).

Figure 3.5 Plastic film cladding, used in mild climates

Source: *El-Behairy, 2015.*

Figure 3.6 Glass or rigid plastic cladding, used in temperate climates

Source: *El-Behairy, 2015.*

The efficiency of natural ventilation, which is proportional to pressure differences (Bot, 1983), depends on the height of the greenhouse if ventilation openings are positioned at the ridge and the sidewall. The higher the ridge and the bigger the distance between ventilators at the ridge and sidewalls, the higher are the pressure differences. On the other hand, wind loads, and the strength of the structural components, depend on the height of the greenhouse, just as the heat requirement depends on the surface area. High greenhouses with large volumes provide better climatic conditions, but also increase the heat requirement if heating is needed.

The design of the greenhouse must be chosen according to the climate conditions and the general design requirements, rather than according to national traditions or imported turnkey models. Simple plastic film greenhouses predominate in warmer subtropical countries (De Pascale and Maggio, 2005). In developing countries, the structure and the shape are often not adapted to the local climate conditions. Low-cost plastic film greenhouses, for example, are designed on the principle of minimum capital and technological input as well as low running costs. These predominate in warmer subtropical countries (De Pascale and Maggio, 2005). However, crops cannot be grown in them year-round, and it is difficult for the yield to fulfil quality standards completely, because of inadequate climate conditions inside the simple greenhouse structures (Baille, 1999, 2001).

Figure 3.7 Simple, low-cost greenhouse structures

Source: *Von Zabeltitz, 2011.*

Figure 3.8 More advanced plastic-covered greenhouse with roof ventilation

Source: *Baudoin, 2018.*

3.1.3 TYPES OF GREENHOUSES

The most frequent greenhouse shapes are (a) saddle roof, (b) sawtooth or shed roof, (c) round-arched tunnel, (d) round arch with vertical sidewall, (e) pointed arch with sloping sidewall and (f) pointed arch with vertical sidewall (Figure 3.9). The best designs for plastic film greenhouses are designs (e) and (f).

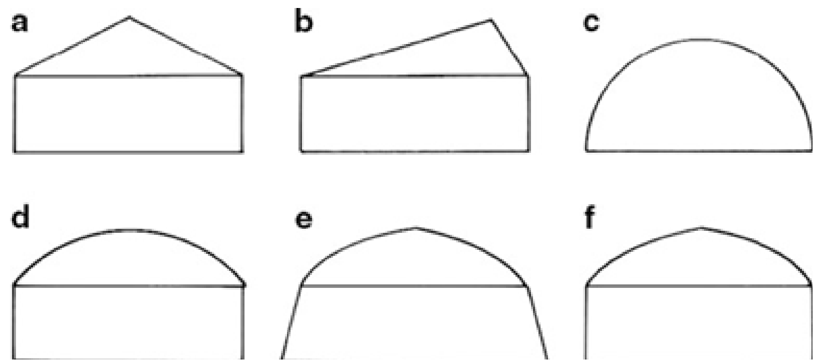


Figure 3.9 Most frequent shapes of greenhouses

Source: *Von Zabeltitz, 2011.*

ROUND-ARCHED TUNNEL GREENHOUSES

Round-arched tunnel greenhouses are still the most commonly used greenhouses in many developing countries with mild climates (Figure 3.10).

The advantages of the single-span tunnels are their relatively simple construction system and their wind resistance, provided they have foundations and the steel tubes are not too weak. However, the disadvantages in yield and quality are significant.

The disadvantages of the round-arched tunnel greenhouses are the following (Von Zabeltitz, 2011):

- The net floor area for plant cultivation is small compared to the ground occupied by the tunnels. The space left between two tunnels is 1 to 3 m (Figure 3.10).
- The plastic film consumption is higher per net floor area.
- In heated greenhouses the surface area is greater and, thus, heat consumption is higher.
- The greenhouse volume is too small for appropriate climate control.
- There is a relatively wide, nearly horizontal area at the top of the greenhouse (1 to 2 m wide), where water condenses and drips into the greenhouse.
- Between 6 and 30 wires are stretched longitudinally along the greenhouse and fastened to the bent pipes. These wires can damage the plastic film.
- Because of the wires, water droplets cannot run off along the inner surface of the film (even if no-drop film is used) and instead, the water droplets drop down where the wires touch the film. Thus, wires should be avoided in greenhouse construction.

- When tall plants (such as tomatoes, cucumbers and roses) are grown, the arched design of the wall means that such plants cannot be grown within one meter of the sidewalls.
- The plants near the sidewall ventilation and the gable grow less than those in the middle of the tunnels. This is caused by lower temperatures, lower humidity near the vents and gables, and wind effects.
- Very often, round-arched tunnels are built without a foundation or the foundations are not sufficiently secured against uplift wind forces. Such tunnels can be destroyed by uplift wind force (Figure 3.10).
- Ventilation efficiency is not sufficient if only the overlapping plastic film and the doors at the gables are "opened". This kind of ventilation must be opened manually. This takes a long time, and the greenhouses can overheat in the morning.

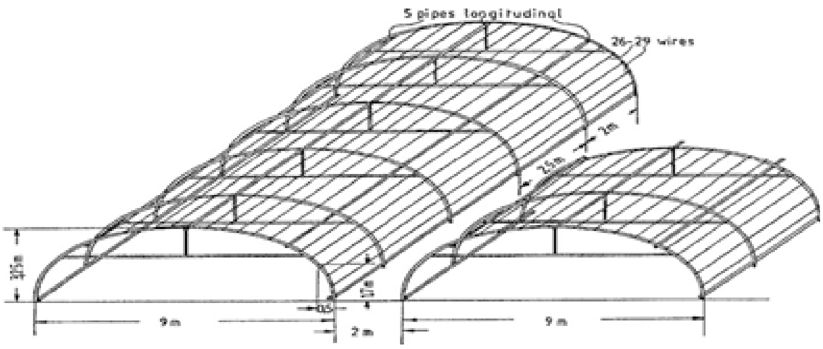


Figure 3.10 Round-arched tunnel greenhouse without solid foundation, not properly anchored in the soil

Source: *Von Zabeltitz, 2011.*

The simple ventilation system of round-arched tunnels, which consists of opening the overlapping film sheets, is not sufficient. If the film has a width of 6.5 m, there should be an opening every 6 m at the sidewall. Thus, the ratio of vent area to the greenhouse floor area is less than 10 percent. For optimum ventilation, the ratio should be more than 20 percent. Even if the vent openings are opened by parting the overlapping film sheets over the entire round-arched surface, the ventilation efficiency is not always sufficient. For adequate ventilation in round-arched tunnel greenhouses, they must have through-ventilation openings at both sidewalls (Figure 3.11). In this case, however, the border effect must be taken into consideration.

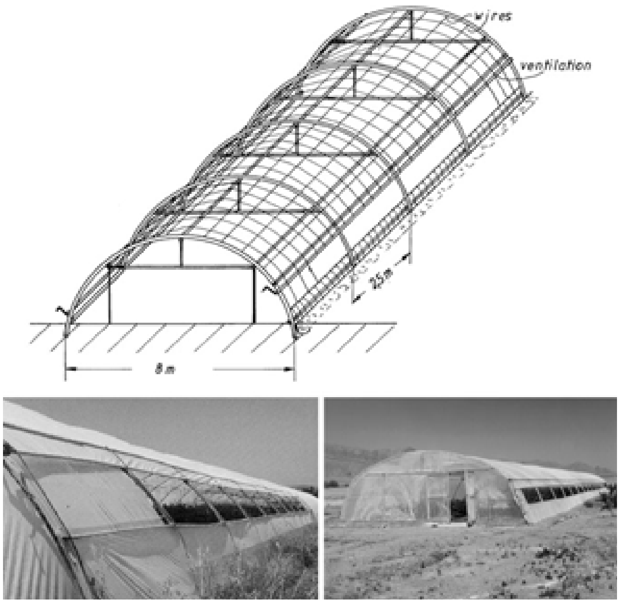


Figure 3.11 Ventilation at both sides

Source: *Von Zabeltitz, 2011.*

ENLARGED TUNNEL GREENHOUSE

If farmers cannot replace the traditional round-arched greenhouses with more appropriate ones, they can improve the existing greenhouses for better climate control, as shown in Figure 3.12. According to Von Zabeltitz (2011), the height of the greenhouse can be increased by connecting pipes of about 1.5 m to the ends of the original truss tubes. In this case it is absolutely necessary to reinforce the anchorage of the greenhouse with concrete point foundations. Effective sidewall ventilation must be installed. The film below the ventilation openings is buried in the soil and filled with gravel. In this way, it works as a gutter to drain off rainwater, and it gives additional stability to the whole construction against uplift wind forces.

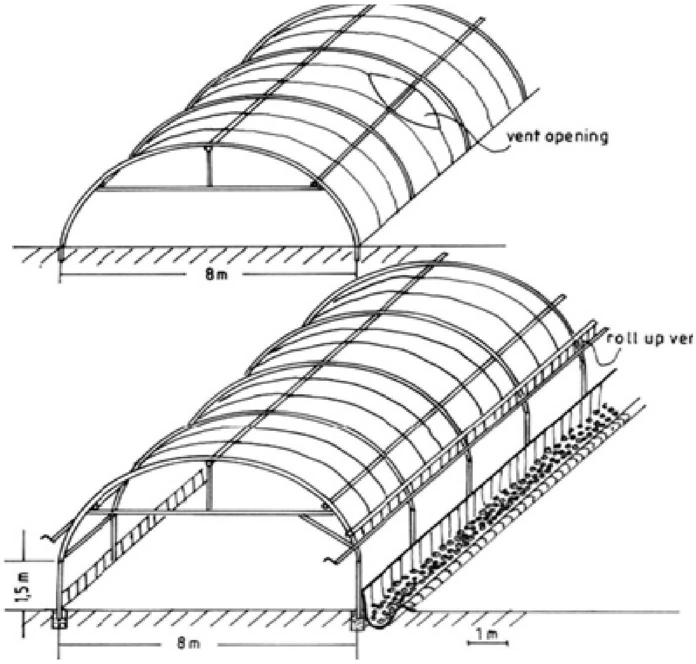


Figure 3.12 Improvement of existing round-arched greenhouses by installing vertical sidewalls

Source: *Von Zabeltitz, 2011.*

POINTED-ARCHED GREENHOUSES

Pointed-arched greenhouses normally have a wider, more or less horizontal zone at the ridge, where water condenses and drips even when special no-drop film is used (Von Zabeltitz, 2011).

MULTI-SPAN GREENHOUSES

Multi-span gutter-connected plastic-film greenhouses fulfil most of the design criteria. They have the following advantages:

- They have a larger volume, and the climatic conditions are better during both day and night-time. (The sidewalls should be as high as possible. Although a sidewall height of 3 m is favourable, wind resistance must be guaranteed.)
- Ventilation with sidewall and gable ventilators can prove sufficient if the total width of the multi-span unit is limited to about 18 m.
- Ventilators can be operated mechanically.
- They allow higher crop density and the border effect is reduced. Vertical sidewalls avoid the loss of space along the sidewalls and allow the use of machines inside the greenhouse. The usable greenhouse area per ground is higher.
- Pointed-arched roofs can be built to reduce dripping.

Small units with only two to three spans can, therefore, be built with sidewall and gable ventilation only if the gutter height is 3 m or more. Multi-span greenhouses with four or more spans require roof or ridge ventilation. Many greenhouses in the subtropics do not have ridge vents, but if insect screens are used the vent openings must be enlarged.

Figure 3.13 shows a pointed-arched steel tube construction with a span width of 5 m and gutter height of just 2 m. Pointed-arched or gothic-arched structures have advantages over round-arched structures because condensed water can more readily flow down along the inner side of the film, reducing dripping on the plants. The sidewall should be 3 m or more. The plastic film at the gutter is fixed and stretched by rolling it up on a steel tube in the gutter. The roof tubes are fixed at the stanchions with clamps in which they are inserted and screwed.

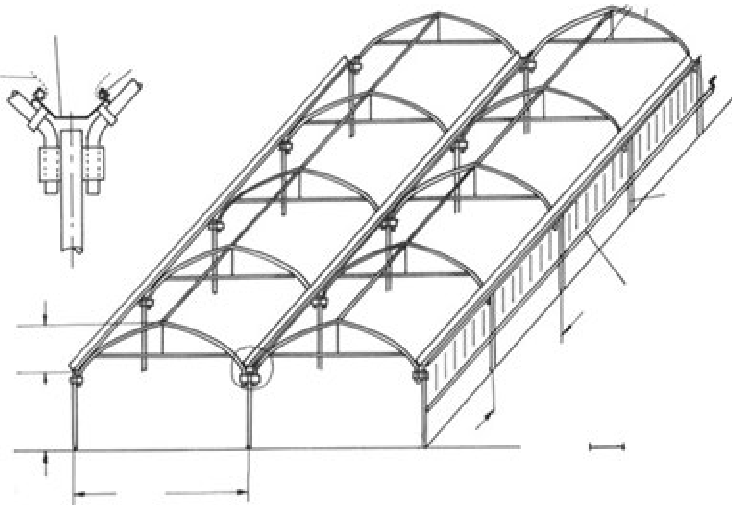


Figure 3.13 Pointed-arched greenhouse

Source: *Von Zabeltitz, 2011.*

The width of the single span depends on the maximum width of the plastic film available in the country. Figure 3.14 shows a round-arched gutter-connected construction with a sloping sidewall to stabilise the construction against wind forces. The plastic film is fixed and stretched by rolling it up on a tube in the gutter profile. The film can also be fastened and stretched at the sidewall without a gutter by rolling it up on a tube. The roof and the sidewall cladding are rolled on one tube. The film is rolled up on the sloping sidewall for ventilation. Round-arched constructions may be easier to design, but pointed-arched constructions are preferable for the plastic film (Von Zabeltitz, 2011).

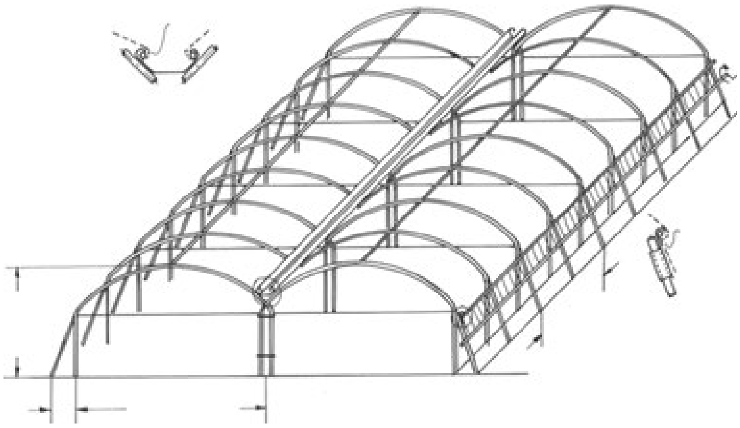


Figure 3.14 Round-arched greenhouse with sloped sidewalls

Source: *Von Zabeltitz, 2011.*

Sloped sidewalls are better if insect screens are installed because ventilators with insect screens need bigger opening areas for sufficient ventilation efficiency (Figure 3.15).

Figure 3.15 Sloped sidewalls covered with insect screens and rolling-up ventilation

Source: *Von Zabeltitz, 2011.*

Figure 3.16 shows the possibility of fastening the plastic film by rolling it up on a steel tube. Both the plastic film at the sidewall ventilation and the plastic film of the roof can be fixed by rolling the film up on one tube.

Figure 3.16 Fixing and stretching both the plastic film of the roof and the ventilation opening on one tube

Source: *Von Zabeltitz, 2011.*

Figure 3.17 shows an example of multi-span greenhouses with reinforcement for wind resistance. Various types roof or ridge ventilation are possible if the greenhouse units have more than two spans and if the total width is more than 18 to 20 m (Figure 3.19).

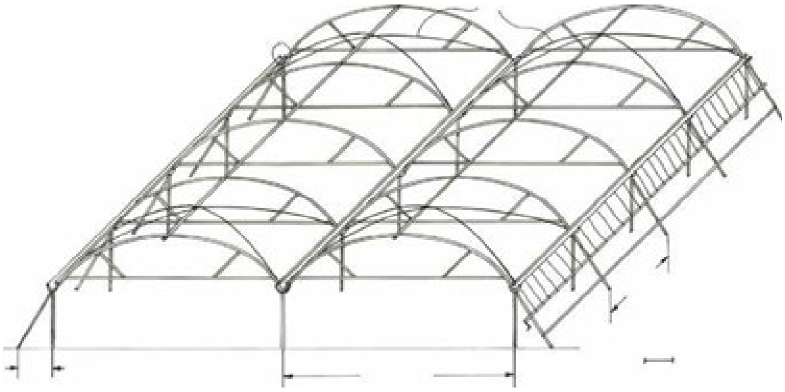


Figure 3.17 The additional stretching of ropes across the roof at the gable ends may have advantages in areas with high wind speed

Source: *Von Zabeltitz, 2011.*

Figure 3.18 Multi-span greenhouse with flap ventilation at the ridge and roll-up ventilation at the sidewall

Source: *Von Zabeltitz, 2011.*

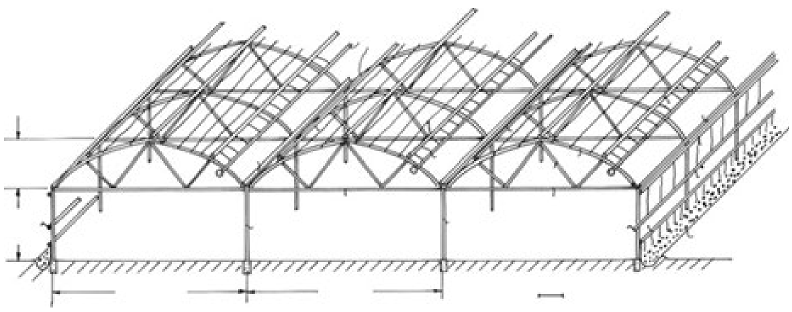


Figure 3.19 Vertical roll-up ventilation at the ridge, which is very effective in hot climates

Source: *Von Zabeltitz, 2011.*

Figure 3.20 shows two kinds of roof ventilation. Both open one-half of the roof. One is linked at the gutter and opens at the ridge. This ventilation must have good resistance against perpendicular wind forces and must be installed tightly. The other opens at the gutter and is linked at the ridge. Both types of ventilation should open a minimum of 1 m high. This means that a sufficiently long and strong rack-and-pinion drive must be installed.

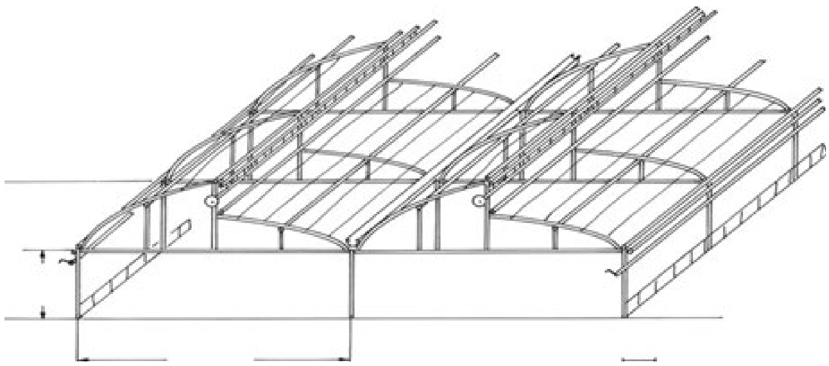


Figure 3.20 Multi-span greenhouse with roll-up side wall ventilation and roof ventilation linked to gutter and ridge

Source: *Von Zabeltitz, 2011.*

All multi-span greenhouses can have a pointed-arched roof, which has advantages for the run-off of condensation. At the sidewall, there is a plastic film fastened to the posts and dug into the soil on the other edge. The film in the soil is filled with gravel, and thus acts as a gutter, while at the same time stabilising the whole structure against uplift forces.

If greenhouses do not have a gutter at the eaves of the sidewall, they must have ditches deep enough to drain off the rainwater. The plastic film at the sidewall must be placed a minimum of 20 to 30 cm into the soil to prevent water from penetrating the greenhouse from the sidewall.

An effective solution is shown in Figure 3.21. The plastic film of the sidewall forms a ditch that is 30 to 40 cm deep. The ditch is filled with 10 to 30 mm of gravel. As a result of this, rainwater can drain off, the sidewall is tight against penetrating water, and the plastic film placed under the ground gives additional stability to the construction.

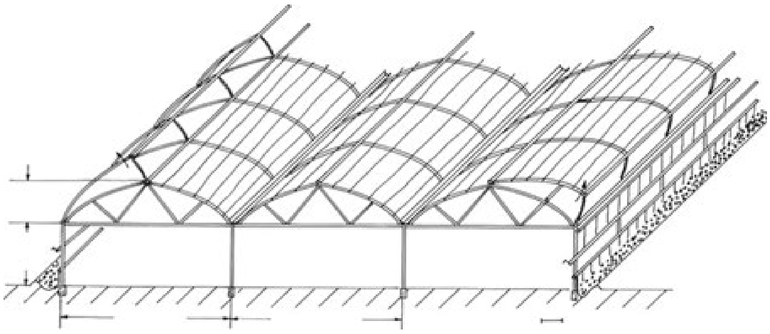


Figure 3.21 Ditch as gutter

Source: *Von Zabeltitz, 2011.*

Greenhouses must have a sufficient longitudinal slope to drain off rainwater into gutters or ditches.

GREENHOUSES FOR TROPICAL LOWLANDS

Greenhouses are very important for tropical regions because they enable producers to avoid the disadvantages of open-air production while increasing yield and quality remarkably. The adverse environmental conditions in the tropics and semi-tropics are more difficult to control than those in the Mediterranean climate. The availability of cost-effective construction materials and plastic film of different widths varies in different countries. According to the materials available, greenhouses can be constructed using wooden poles, timber profiles and/or steel tubes. The dimensions of the greenhouse also depend on the available dimensions of materials and plastic film. Greenhouse design varies from simple structures for small-scale farmers to more industrialised multi-span structures for large-scale farmers. In many developing countries, small-scale farms are the majority. Therefore, appropriate, cost-effective structures must be designed.

According to Von Zabeltitz (2000), greenhouses for tropical lowlands should have the following characteristics:

- Crop protection from rain, wind and extreme global radiation is necessary. This could include impermeable cladding material and UV-stabilized, long-life plastic film, which is sufficient for most of the tropical lowland greenhouses.
- Crop protection from birds and insects is also necessary.
- The greenhouse must have very efficient ventilation, with ventilation openings at sidewalls and the ridge. (Ridge ventilation is absolutely necessary.)
- The ratio of greenhouse volume to ground floor area should be as large as possible, and gutter height should be a minimum of 3 m.
- The higher the structure, with ridge vents, the higher the ventilation efficiency, because of the chimney effect.
- Gutters are necessary to drain off rainwater and prevent rainwater from penetrating the greenhouse.

- The roof at the gutter should overlap the sidewall to prevent sloping rainfall from penetrating the greenhouse.
- Construction must be resistant to wind and crop loads.
- The foundation of the construction should guarantee wind resistance and prevent stanchions from rotting.

GREENHOUSE CONSTRUCTIONS FOR ARID REGIONS

Greenhouses for arid regions must protect crops from excessively high irradiation, low temperatures in winter, wind, sandstorms and insufficient humidity (Von Zabeltitz, 2011). In arid regions greenhouses have forced ventilation, using fans, in combination with evaporative cooling. A heating system is also necessary for cold nights with frost. In the case of flower production, the cladding material is often doubled with an outside shade net. Permanent outside shading is less suitable for vegetable cropping in the main winter season. Internal or external moveable shading systems have advantages for light control, for example in the early morning. Moveable inside shading can be used as thermal screening to reduce heat loss in winter. Shading systems are also necessary to reduce incoming radiation and to improve the cooling efficiency (figures 3.22 and 3.23).

Figure 3.22 A greenhouse structure for desert regions in Kuwait, covered with rigid plastic sheets and equipped with fan and pad cooling

Source: *Von Zabeltitz, 2011.*

Figure 3.23 A round-arched structure covered with plastic film and permanent shading net, ventilated and cooled by fan and pad system

Source: *Von Zabeltitz, 2011.*

HIGH-TECHNOLOGY GREENHOUSES

According to the Department of Primary Industries in New South Wales (2018):

High-level greenhouses have a wall height of at least 4 m, with the roof peak being up to 8 m high. These structures offer superior crop and environmental performance. High-technology structures will have roof ventilation and may also have sidewall vents. Cladding may be a plastic film (single or double), polycarbonate sheeting or glass. Environmental controls are almost always automated. These structures offer enormous opportunities for economic and environmental sustainability. Use of pesticides can be significantly reduced. High-technology structures are visually impressive and, internationally, are increasingly being used in agribusiness. Although these greenhouses are capital intensive, they offer a highly productive, environmentally sustainable opportunity for an advanced fresh produce industry. Wherever possible, investment decisions should consider installing high-technology greenhouses (Von Zabeltitz, 2011), taking into consideration the cost-effectiveness in line with the targeted consumer price market.

Figure 3.24 Multi-span greenhouse with high technology

Source: *Castilla et al., 2004.*

3.2 BEST PRACTICES AND SANITATION MEASURES TO PREVENT PESTS AND DISEASES

It is important to understand that technology alone will not suffice to ensure sustainable intensification of greenhouse crop production.

Appropriate cultivation practices, pest and disease control and sanitation measures are prerequisites to sustained productivity and quality.

Growers should pay attention to the following best and smart practices, which should be observed:

- Site selection, in terms of soil quality and drainage, access to fresh water for irrigation and cooling, climatic advantages and market outlets.
- Planning the production calendar according to market demand: selection of crops, cultivars and growing seasons.
- Proper management of the nutrient solution in the case of hydroponics or substrate cultivation.
- Production of quality seedlings (plantlets) from a reliable seed source (certified seed).
- Plant distance, plant training and pruning for best area and volume occupation.
- Adequate irrigation and fertilization scheduling.
- Non-chemical pest control, including biological control (when applicable) as well as mass insect trapping, physical barriers like double entry doors or SAS (safety access system), insect-proof nets on all greenhouse openings. (The greenhouse should be properly sealed with no holes in the covering material.)
- Overall sanitation and hygiene measures are equally important to reduce pest and disease problems and avoid reliance on chemical pest control. This includes the installation of a footbath at the entrance of the greenhouse to disinfect the shoes and a sink to wash hands before entering. The greenhouse surrounding area should be kept clean of weeds, which are potential host plants for insects and a reservoir of virus and fungal diseases that could be transmitted to the crops inside the greenhouse. In between two crop cycles, the greenhouse structure and cladding material should be properly disinfected from the inside.
- Greenhouse access should be limited to authorized personnel, and visitors should wear protective clothing for hygiene.

It should be noted that the region lacks sufficient qualified professional field staff. To address this constraint, more attention should be paid to vocational training of foremen and skilled labour to implement best and smart practices.

3.3 SOILLESS CROP PRODUCTION

The scarcity of water resources was the main factor that drew attention to the use of intensive agriculture in arid lands. Protected cultivation, which started in the late 1970s and intensified in the mid-1980s, was the first step. The next step was to maximise crop yield per square meter of soil and per cubic meter of water by using soilless culture systems (Zayd, *et al.*, 1989). Recently, soilless culture has become even more important in arid lands for a number of reasons. Continuous cultivation of crops has resulted in poor soil fertility, which in turn has reduced the opportunities for natural soil fertility to build up microbes and led to poor yield and quality. In addition, conventional open-field crop cultivation is difficult as it requires large amounts of land, water and labour. Finally, soilless culture is needed to increase water use efficiency in crop production (Abou-Hadid *et al.*, 2004).

Soilless agriculture means growing plants in the absence of land, where the soil is used as a support to the system, rather than as the medium for plant growth. This technique obviates the problems and difficulties associated with open-field production. Soilless culture, along with greenhouse production, is possibly the most intensive method of crop production in today's agricultural industry.

In soil-based protected cultivation, the high levels of crop production and continuous cropping inevitably lead to problems of pests and diseases in the soil. This eventually reduces crop yield, and cultivation can only continue if some form of soil sterilisation or crop rotation takes place. Steam sterilisation is not economically viable and is not efficient. The use of methyl bromide is banned in many European states and will be banned in other states as well. Thus, for production to continue, there inevitably must be a move towards some form of soilless culture or soil-replacement cultivation.

The use of soilless culture has substantially increased during the last decade as it intensifies horticultural production and provides high crop yields, even in areas with adverse growing conditions.

Soilless culture techniques provide several advantages, which can be summarised as follows (Olympios, 2011):

- standardisation of the culture and of the root environment in particular;
- eliminating the issue of soil infection and hence the danger of disinfectant residues;
- drastic reduction of energy input for the conditioning of the root environment;
- crop production is made possible where the soil is unsuitable;
- drastic reduction of water consumption;
- efficient use of nutrients;
- better control of vegetative and generative plant development;
- earlier and higher level of production;
- qualitatively better production;
- rationalisation of labour;
- more possibilities for culture mechanisation and automatic control.

3.3.1 NEED FOR ADOPTION OF SOILLESS CULTIVATION IN ARID LANDS

INCREASED PRODUCTIVITY

The matter of increased yields with soilless culture should be examined carefully. It is true that precise control of plant nutrition through soilless culture results in higher yields and quality, but this does not necessarily mean that yields from the best soil-based culture are inferior. Nevertheless, it is unlikely that the fast increase in soilless culture in Netherlands (the) and other European countries would have occurred unless commercial growers were confident that yield would increase and help offset the additional costs of soilless culture.

It is understandable that if there are soil problems (poor soil, saline soil, toxic soil, etc.), then soilless culture will produce much better crops. Many reports have been published during the last 15 years comparing the results of soil-based and soilless culture. Most of them show advantages in soilless systems, usually due to a combination of factors such as reduced labour, higher yields and greater uniformity of quality due to uniform conditions of growth. It should be noted, however, that in many experiments, the crops in soil-based cultivation were not managed properly (Olympios, 2011).

CONTROL OF PLANT NUTRITION

The accurate control of plant nutrition is one of the most important advantages of soilless culture because the concentration of nutrients can be controlled according to the crop, the environment, the stage of plant growth, etc. Elements which are harmful to plants above certain concentrations (such as Mn, B, Zn, Cu and Pb) can also be controlled.

Another important advantage related to plant nutrition in soilless culture is the uniformity with which nutrient elements can be supplied to the substrate. This is particularly true with water culture and the more sophisticated systems, and less true for the aggregate cultures, especially the simplest ones using surface drip irrigation systems (sand culture, etc.).When using water cultures or aggregate cultures with inert substrates, the grower determines the level of nutrients supplied to the new crops. This is not the case with soil-based culture, where in many cases excess nutrients remaining in the soil from the previous crops produce salinity.

Another advantage of soilless culture related to plant nutrition is the ability to control the pH and the electrical conductivity (EC) of the nutrient solution according to the requirement of the crop and the environmental conditions. Similar control in soil cultures is very difficult and expensive (Olympios, 2011).

CONTROL OF SOIL PATHOGENS

In greenhouses, agricultural practices in the soil are likely to increase soil-borne pathogens such as nematodes and to accumulate salinity. Greenhouses are cropped on an essentially continuous basis, with restricted possibility for suitable rotations. The limited crop range and continuous production result in reduced soil fertility and rapid build-up of soil pests, which hamper production and require intensive use of chemicals (Hanafi & Papasolomontos, 1999).

Moreover, the present conventional growing system in soil wastes a lot of fresh water due to run-off and deep percolation. In arid countries, rapid evaporation of water from the soil surface may also lead to salinity problems. Soilless culture (hydroponics) would be the answer to many such constraints and to successfully obtaining high quality and yield. In the absence of soil, in hydroponic systems, soil-related constraints are likely to disappear, thus eliminating the need for expensive soil sterilisation processes and the application of hazardous agro-chemicals in greenhouses. Hydroponic offer opportunities to provide optimal conditions for plant growth and, therefore, higher yields can be obtained compared to conventional soil-based agriculture (Moustafa *et al.*, 2007).

WATER ECONOMY AND CONTROL

Water is the most important factor in crop production. It is a limiting factor not only of crop availability but also of crop quality and cost. In hot, arid regions, protected crops require large amounts of water for production.

The advantage of soilless culture related to the ease of irrigation applies mainly to certain soilless systems, such as nutrient film technique (NFT) and other true hydroponic systems (where the plants have their roots immersed into the nutrient solution) and to sub-irrigated substrate culture, and is not fully applicable to other modalities of soilless cultures using various inorganic or organic substrates. The frequency and duration of irrigation are much more critical in substrates with low water holding capacity, compared to soil.

Concerning water saving, certain soilless systems, for instance closed or recirculated systems, undoubtedly economise water because drainage and evaporation from the surface are eliminated by the design and operational scheme of the systems (NFT, "closed" systems and sub-irrigated soilless culture). With soilless culture, water supply is controlled more accurately.

Furthermore, water culture and sub-irrigated substrate systems eliminate the need for the time-consuming task of checking and cleaning irrigation nozzles, thus reducing labour considerably. On the contrary, crops grown on substrates and soil require frequent examination of trippers as these can easily be blocked by calcium carbonate or other compounds, especially with a "hard" water supply. In water culture and sub-irrigated substrate systems, nozzle blockage can be eliminated either by acidification of the nutrient solution or by pre-treatment of irrigation water (Olympios, 2011).

REDUCTION OF LABOUR REQUIREMENT

Soilless production excludes all cultural practices associated with the cultivation of the soil, sterilization of soil, weed control, etc. Although the labour requirement for soilless culture is not the same in all soilless systems, generally, soilless culture reduces required labour input, with variations according to the system, degree of automation, type of substrate, number of crops raised on each substrate, etc. (Olympios, 2011).

STERILISATION PRACTICES

Greenhouse soil must be free from any soil-borne pathogens before establishing a new crop. Sterilisation is difficult and costly, but necessary. It is justified because the greenhouse business requires high investment in structures, facilities, plant materials, running costs, etc.; and obtaining maximum yields and returns is necessary in order to have an economically viable operation. The most effective method of soil sterilisation is steaming, but this method is expensive due to its high energy and labour costs.

As such, this method is rarely used. Chemical sterilisation is less expensive but not without disadvantages. For example, formaldehyde produces fumes which are highly phytotoxic. The most important component of formaldehyde, methyl bromide, is a very toxic substance to handle and leaves chemical residues (bromide ions) which are absorbed by the crop and cause environmental pollution.

Soilless crop cultivation is, therefore, of great advantage as there is no need for sterilisation when materials and substrates are used only one time, as the spread of disease is avoided. In "closed" soilless culture (depending on the system), the need for sterilisation varies. For example, to clean "true hydroponic" culture structures, following the removal of all debris, a diluted solution of formaldehyde is used, followed by rinsing with clean water. In the NFT system, the film that forms the gullies can be replaced. When solid substrates are used, steam or chemical sterilisation should be used if the material is to be used again. In this case, the application of both is easier and more economical. In all cases, sterilisation of soilless culture systems is easier than soil sterilisation (Olympios, 2011).

CONTROL OF ROOT ENVIRONMENT

Accurate control of root temperature and root oxygen supply are easier to achieve in soilless cultivation (Olympios, 2011).

MULTIPLE CROPS PER YEAR

Due to the absence of the cultivation techniques (such as soil cultivation and soil sterilisation), the time interval between crops is short and the number of crops per year is increased in a given production area (Olympios, 2011).

UNSUITABLE SOIL

Soilless culture offers an ideal alternative to soil culture when there is no soil available at all or when the soil is unsuitable for crop production due to high salinity, toxic substances in the soil or an accumulation of soil pathogens (Olympios, 2011).

3.3.2 SOILLESS CULTURE SYSTEMS IN ARID LANDS

Soilless culture is divided into three major branches according to the root growing media:

- hydroponics
- aeroponics
- substrate culture.

HYDROPONICS

Hydroponics is a technology for growing plants in nutrient solutions (water that contains fertilisers). There are different types of hydroponics according to the movement of the nutrient solution. These are described below.

DEEP WATER CULTURE

In this system, the plant roots grow in containers filled with water containing fertilisers (static water). The water is mixed with a nutrient solution, and oxygen is supplied to the plants through the nutrient solution using an air pump or by mixing water with air. The plants float on the nutrient solution by means of a polystyrene sheet.

NUTRIENT FILM TECHNIQUE (NFT)

In this system, the roots of the plants grow in a shallow solution of water and nutrients inside polyethylene sleeves or tubes laid on a sloped bed. The nutrient solution is pumped into the channels in a thin film, and the excess is collected and returned to the catchment tank (Figure 3.25).

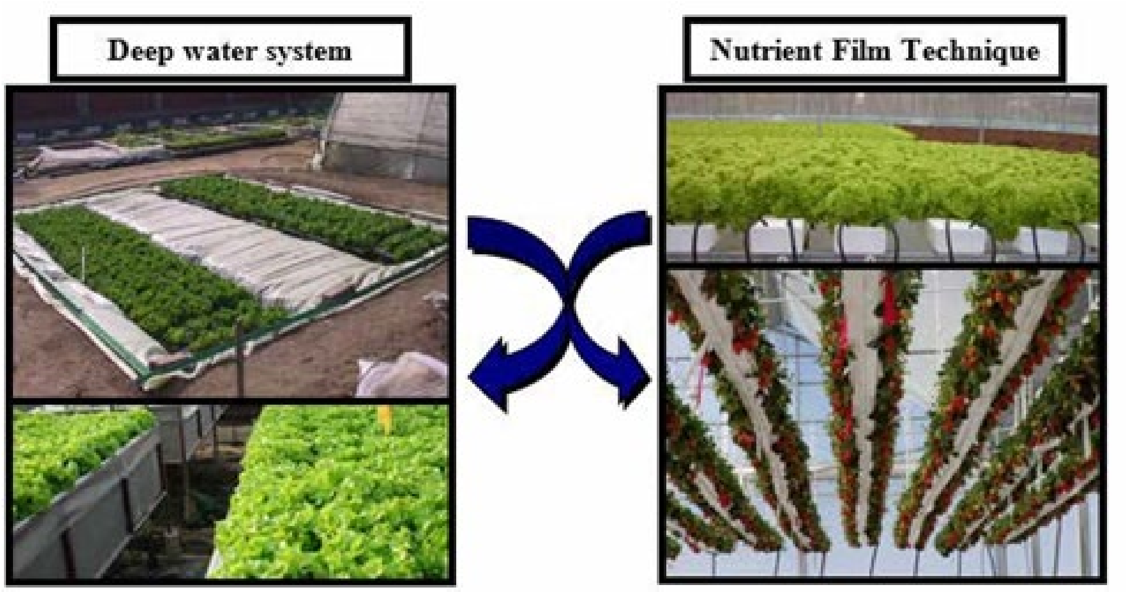


Figure 3.25 Different systems of deep-water culture and nutrient film technique

Source: *El-Behairy, 2015.*

AEROPONICS

In this system, the nutrient solution is sprayed as a fine mist in sealed root chambers. The plants are grown in holes in panels made of expanded polystyrene or another material. The plant roots are suspended beneath the panel, enclosed in a spraying box. The box is sealed so that the roots are in darkness (to inhibit algal growth) and to maintain saturation-level humidity (Figure 3.26). A misting system sprays the nutrient solution over the roots periodically. The system is normally turned on for only a few seconds every 2 to 3 minutes. This is sufficient to keep roots moist and the nutrient solution aerated (Abou-Hadid *et al.*, 2004).

Figure 3.26 Aeroponic crop cultivation

Source: *Abou-Hadid et al., 2004.*

SUBSTRATE CULTURE

In this system, a solid medium provides support for the plants. As in liquid systems, the nutrient solution is delivered directly to the plant roots. Substrate culture is divided into two major systems according to the drainage procedure, as described below.

OPEN SYSTEM

In open systems, the nutrient solution is applied to the plants and is then drained off as waste (Figure 3.27). Because the leached or drained solution is not redirected into the feeder tank, it does not require monitoring and adjustment. Once mixed, it is generally used until depleted. Also, the quality of the irrigation water is less critical. Up to 500 ppm of extraneous salts is easily tolerated, and for some crops (tomatoes, for example) even higher salinities are permissible, though not desirable. The growing medium should be monitored, particularly if the irrigation water is relatively saline or if the operation is located in a warm, highly sunlit region. Enough irrigation water is used to allow a small amount of drainage or leaching from the bags, in order to avoid salt accumulation in the medium. This drainage should be collected and tested periodically for total dissolved salts (Abou-Hadid *et al.*, 2004).

CLOSED SYSTEM

Closed systems work in the same way as open systems, with the important difference that the nutrient solution which runs off after each application is collected and recirculated for reuse.

Closed systems are economical in the use of nutrients but require frequent monitoring and adjustments of the nutrient solution. Measuring electric conductivity (EC) is a convenient means to check the total salt concentration but provides no data on the concentration of major elements nor the amounts of trace elements present. As such, periodic chemical analyses are required, usually every two or three weeks for major elements and every four to six weeks for trace elements (Figure 3.27).

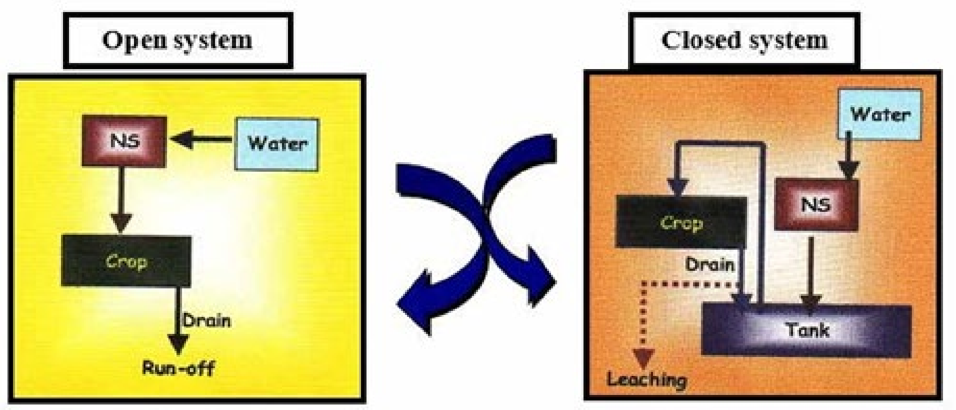


Figure 3.27 Circulation of nutrient solution in open and in closed hydroponic systems

Source: *El-Behairy, 2015.*

There are several constraints regarding soilless culture in arid lands. These are summarised below:

- high temperatures during most of the year;
- scarce availability of soft water;
- high quantity of water required for cooling;
- lack of availability of necessary equipment in the country;
- unavailability of the soluble fertilisers for making the nutrient solution in the country.

3.4 SUBSTRATES

3.4.1 GROWING MEDIA FOR HORTICULTURE CROPS IN ARID LANDS

Growing media serves a number of purposes, as listed below:

- it is a reservoir for plant nutrients;
- it is a reservoir for water for the plants;
- it provides gas exchange between the roots and the atmosphere outside the root substrate;
- it provides support for the plants.

Some substrates can provide all four functions, but not necessarily at the required levels of each. For example, sand provides excellent support and gas exchange but has insufficient water and nutrient supplying capacity (Olympios, 2011).

3.4.2 CHARACTERISTICS OF SUBSTRATES

CAPACITY TO HOLD WATER

The capacity to hold and drain surplus water depends on the medium's texture, the size and form of its granules, and its permeability. Smaller granules have more surfaces and are close to each other, and therefore, can hold more water than larger granules. Uneven granules have more surface area than even granules or round granules and thus have higher water-holding capacity. Consequently, the granules should be of an appropriate size to hold the amount of water suitable for crop growth (Abou-Hadid *et al.*, 2004).

GOOD AERATION AND GOOD DRAINAGE CAPACITY

The substrate should have good drainage capacity for removing the surplus water and ensuring good aeration around the roots. Substrates with fine granules, which impede the movement of oxygen, reduce the overall aeration in the growing environment and, thus, asphyxiate the plant roots, should be avoided (Abou-Hadid *et al.*, 2004).

FREE FROM HARMFUL OR POISONOUS MATERIALS

The substrate should be free from any material which may harm plant roots or affect plant growth, such as sand and small limestones containing calcium carbonate. This should be avoided as it can increase the pH of the nutrient solution above seven. This increase leads to the sedimentation of iron and phosphorus, resultant in deficient uptake (absorption) at the level of the roots, causing deficiency symptoms although these elements are available in the solution.

PLANT SUPPORT

The substrate serves as root support media and fixes the plants properly. This depends on the texture of the substrate, which should be medium-heavy to fix plant roots (Abou-Hadid, *et al.*, 2004).

FREE FROM DISEASE-CAUSING PESTS AND INSECTS

The substrate should be free from different pests and insects, so that plants are not infected with different diseases (Abou-Hadid *et al.*, 2004).

FREE FROM SALINITY

The substrate should be free from salinity to avoid affecting the growing plants. For instance, wood dust usually contains a high concentration of sodium chloride as the wood is soaked in a salt solution for a long period (Abou-Hadid *et al.*, 2004).

FREE FROM WEED SEEDS

This is to avoid the growth of weeds, which will compete with the main crop for nutrition and water. Weeds may also host some diseases, which could infect and damage the growing plants (Abou-Hadid *et al.*, 2004).

SLOW DECOMPOSITION PROCESS

When using an organic medium, it should have a slow decomposition rate so that it can be used for the longest period possible. This will reduce the cost of changing the substrate more frequently (Abou-Hadid *et al.*, 2004).

EASILY TRANSPORTED, HANDLED AND LESS EXPENSIVE

It is important to select a substrate that is available in several locations to facilitate its handling and transportation. This will reduce transportation costs. The price of the substrates should be affordable and cost-effective (Abou-Hadid *et al.*, 2004).

3.4.3 TYPES OF SUBSTRATES

Substrates can be classified as follows:

Inert media: A solid, inert material, such as perlite, sand, rock wool, volcanic gravel and pumice, that supports the plant and provides air and water to the roots.

Organic media: A natural, organic material, such as peat moss, coconut fibre, coco peat, rice husk and wood bark that supports the plant.

There are several raw materials that are used as substrates. Such materials differ from one another in their physical characteristics. Due to variations and multiplicity in the forms and types of materials available in the surrounding environment, criteria should be developed for selecting the appropriate substrate (Olympios, 2011).

ORGANIC SUBSTRATES

Peat moss

Globally, peat moss is the most widely used substrate. It is a decomposed organic material found in peat moss mines in humid locations throughout the world. It is used alone or mixed with other substrates such as vermiculite or sand. Peat moss has high capacity to absorb water (about 8-fold its weight at saturation level) and good drainage, low acidity, a high percentage of organic matter (94 to 99 percent) and high porosity (95 to 98 percent).

Rice husk

Rice husk provides necessary aeration for roots of different plants and it can be mixed with other substrates to improve air content and drainage capacity. It is lightweight and has a medium level of water-holding capacity.

Coconut fibres

Coconut peat and fibres have recently been used as substrates for soilless agriculture. They are durable and can be used more than one year with no change in physical characteristics. Coconut fibres have good water-holding capacity and provide enough air content to the substrate.

NON-ORGANIC SUBSTRATES

Sand

Sand is one of the best and oldest substrates for growing plants. Sand containing lime should not be used due to its high content of calcium carbonate, which welds the sand granules together and changes the physical characteristics of the sand. Coastal sand should also not be used due to its high salt content. Sand from granite or silicone origins are better agricultural substrates. The diameter of sand granules is an important factor. Course sand does not hold sufficient moisture, and very fine sand does not allow for sufficient aeration. Sand has good drainage capacity, but it does not hold much water. Therefore, it should be mixed with peat moss or compost.

Vermiculite

Vermiculite is dehydrated iron, aluminium and magnesium silicate, which is obtained from metallic chips from mica mines in Africa, Australia and America. The metallic chips are heated to 1 000 ºC, which fragments the metal, making it into small, light pieces with good porosity and characteristics appropriate to soilless agriculture. Vermiculite has high water-holding capacity and is best mixed with other materials to reduce permanent wetness. Vermiculite contains magnesium and potassium, which the plant can absorb.

Perlite

Perlite is a grey or white volcanic stone consisting of aluminium silicate, sodium and potassium. Perlite is ground and heated to 900 to 1 000 °C, causing the expansion and swelling of the granules. Perlite is widely used either alone with good results or mixed with other substrates, such as peat moss, to grow several vegetable crops, seeds, flowers and indoor ornamental plants. Perlite has many advantages, including good capillary porosity, which facilitates sub-surface irrigation and good drainage and water-holding capacity. However, it should be irrigated several times per day to guarantee water availability and nutritional elements needed by the plants. It has stable physical consistency, good aeration and is lightweight.

Calcined or expanded clays

Montmorillonite clay minerals, when heated to approximately 690 ºC, form calcined clays. The pottery-like particles formed are six times as heavy as perlite. Calcined clays have relatively high cation exchange and water-holding capacity. This material is a very durable and useful amendment (Verdonck and Demeyer, 2004).

Pumice

Pumice is a direct product of acidic volcanism. It is a highly vesicular volcanic glass, silicic in composition, and occurs as massive blocks or unconsolidated, fragmented material. The vesicles are glass-walled bubble casts, which give pumice a low density compared to natural glass. Pumice, the commercial term for fine-grained, fragmented pumice with shards under 2 mm in diameter may be deposited some distance from the source.

Pumice is formed from silicic lavas rich in dissolved volatiles, particularly water vapour. On eruption, the sudden release of pressure leads to the expansion of volatiles which, in turn, generates a frothy mass of expelled lava. This mass may solidify on contact with the atmosphere as a vent filling or flow or may be shattered by a violent eruption (El-Behairy, 2015).

Pumice is chemically similar to Perlite except that it contains calcium carbonate, which reacts with the acid, reducing the size of the particles. Because of the reduced size of the particles, the substrate can become compacted if it is used for a long time. It is heavier than perlite and does not absorb water easily nor hold water for a long period. Pumice has many advantages such as high strength-to-weight ratio, insulation and high surface area, which result from the vesicular nature of this rock. It has good aeration and it is easy to clean and purify (Verdonck and Demeyer, 2004).

Foamy rock

This is a silicon rock of volcanic origin. It contains aluminium, potassium, sodium, traces of iron, calcium and magnesium. The material has several gaps, which form when hot vapour escapes before the volcanic lava cools down. Foamy rock is available in its natural form. It does not need heating, just breaking and grinding the granules to the appropriate size. Some characteristics include good aeration, chemical similarity to perlite and low water absorption and holding capacity.

Rock wool

The use of rock wool in agriculture has spread quickly, particularly in Europe where it is used to produce many

vegetables and ornamental crops.
Rock wool is a fibre produced from volcanic rocks, which contains diabase (60 percent), limestone (20 percent) and coal (20 percent). The mixture is melted at a very high temperature and then spun in a centrifuge into threads which are 5 microns in diameter. The threads are then compressed and divided into the required sizes. During the cooling process, phenol is added to help bind the rock wool into a porous substrate.

Rock wool is produced in several forms used for different purposes, as follows:

- Germination cubes: These can be single or aggregated cubes.
- Seedling blocks: These are used for seed germination or to grow young seedlings.
- Agricultural slices: To which seedlings of proper size are transferred, and where plants complete their life cycle.
- Loose (unpacked) rock wool: This used as a substrate in pots or is mixed with other substrates to improve aeration and water-holding capacity.

Some characteristics of rock wool are:

- Dry rock wool does not contain any nutritional or non-nutritional solution.
- Sterilised rock wool is free of pests, insects and diseases.
- It is very light but solid. This facilitates its preparation and processing.
- It has high porosity (97 percent of the total size), which facilitates drainage.
- Rock wool facilitates disposal (leaching) of salt sediments by adding water (only in open systems).
- It is easy to sterilise and can be used for more than a year.

3.4.4 SUBSTRATE MIXTURES

The characteristics of the substrate greatly affect the success of the agricultural operation as they determine the balance between the water needed for plant growth and the air necessary for the roots to breathe. Substrates, therefore, must have both small gaps, to help hold water, and large gaps, to ensure there is sufficient air for plant growth. The substrates mentioned above can be used alone or can be mixed to attain the best characteristics for plant growth. Some of the most important characteristics of substrates, which should be assessed, are the following:

- weight
- water-holding capacity
- acidity (pH)
- salt concentration
- apparent density
- cation exchange capacity
- stability.

Some substrate mixtures have been tested and have shown good results. The ratios of some of these mixtures are provided in the table below:

Table 3.1 Substrate mixtures

Substrate	Mixture ratio
Peat moss: perlite: sand	2:2:1
Peat moss: perlite	1:1
Peat moss: sand	1:3
Peat moss: sand	3:1
Peat moss: vermiculite	1:3
Peat moss: perlite	1:4

Source: *El-Behairy, 2015.*

3.5 POTS AND CONTAINERS FOR HYDROPONIC CULTIVATION

3.5.1 POLYSTYRENE POT SYSTEM

There are two main systems for the polystyrene pot system: the vertical pot system and the simple pot system.

VERTICAL POT SYSTEM (CONDENSING SYSTEM)

ICARDA-APRP introduced different production systems for different crops to small growers in the APRP region. For the production of cash crops, such as strawberries and beans, the vertical soilless production system was adapted to maximize growing space. Vertical pot strawberry production has been investigated for the last four years in Bahrain, Kuwait, Oman and Saudi Arabia and, more recently, in Egypt. The system has proved promising in terms of productivity, cost and water savings. The fundamental structure of the system is the columns, which consist of 8 to 12 polystyrene growing containers placed on top of each other, as seen in Figure 3.28. These columns of polystyrene pots are installed in sloped channels lined with polyethylene sheets to collect the excess nutrient solution. At the end of the channels is a PVC tube that conducts the excess nutrient solution to the filter and then to the nutrient solution tank. One-inch PVC tubes inside the pots support the columns. The pots are filled with substrate (peat moss: perlite at 1:4 v/v). The crops are planted in the four corners of these containers. The irrigation water and nutrition solution are applied to the plants using drip irrigation, and the excess water is recirculated in a closed system. The growing containers are made locally, and the system can be installed in any greenhouse or even in the open field (El-Behairy, 2015).

The production of strawberries in the vertical hydroponics system has been quite successful. The hydroponics system has shown the following advantages over traditional soil-bed production (El-Behairy, 2015):

- 30 to 50 percent savings in the cost of production materials;
- more yield per unit of water;
- double the yield per square meter of land area;
- longer production season;
- increased income due to early-season production when prices are high;
- far less incidence of pests and diseases, thus requiring fewer chemicals and producing better quality fruits.

Figure 3.28 Vertical pot system

Source: *El-Behairy, 2015.*

SIMPLE POT SYSTEM

For the production of cash crops, such as tomato, pepper and cantaloupe, the recirculation pot system is adapted to maximize growing space by growing the crops in polystyrene pots. This technique has also been investigated for the last four years in Bahrain, Kuwait, Oman and Saudi Arabia and, recently, in Egypt. Like the vertical system, it has proved promising in terms of productivity, cost and water savings (Figure 3.29). The fundamental structure of the system is simple: polystyrene containers are inserted in a sloped channel lined with polyethylene sheets, as seen in the photo. The crops are planted in containers with a mixed substrate of perlite and peat moss (4:1 v/v). The irrigation water and nutrition solution are applied to the plants using drip irrigation, and the excess is recirculated in a closed system (El-Behairy, 2015).

Figure 3.29 Simple pot system cultivated with tomato seedlings

Source: *El-Behairy, 2015.*

3.5.2 POLYETHYLENE CONTAINERS

Different types of polyethylene containers are suitable for substrate culture in arid lands. Different shapes of containers are used for different substrate systems, as described below:

OPEN-TOPPED VERTICAL CONTAINERS

This type of container is suitable for substrates with good water-holding capacity as it permits a longer column within the container for growing large plants and allows the water to drain by gravity (figures 3.30 and 3.31).

These containers have a few holes 5 cm from the bottom to allow the water to drain. The container is filled with small gravel up to 5 cm and filled the rest of the way with the chosen substrate. If an open system is used, the containers are installed on a bed covered with polyethylene sheets and the drain water is collected and reused. If a closed system is used, a gutter is installed, and the containers are placed inside the gutter. The drain water is collected and delivered to the nutrient solution tank, after filtering (El-Behairy, 2015).

Figure 3.30 Container system using polyethylene bags

Source: *El-Behairy, 2015.*

Figure 3.31 Container system using polyethylene pots

Source: *El-Behairy, 2015.*

HORIZONTAL BAG CONTAINERS

Substrates that cannot hold water, such as perlite, are used with horizontal bags. (Figure 3.32) The bags have a short side, and there are holes at the bottom to drain the excess water. When these bags are filled with water, some of the holes will be blocked, and some water will remain at the bottom of the bags to supply the roots with water and nutrients (El-Behairy, 2015).

Figure 3.32 Strawberry and sweet pepper cultivated in horizontal bags

Source: *El-Behairy, 2015.*

3.6 WATER QUALITY CONTROL

The best water for substrate cropping is rainwater or water condensed from moisture-laden air. Water from these two sources has virtually no dissolved substances in it. Consequently, the water does not cause excess ions to build up in the substrate. In arid lands, fresh water, which is scarce, can be mixed with less pure water to provide blended water in which the concentration of dissolved substances is still acceptable. If substances in the water are supplied to the crop faster than the crop can remove them, the excess will accumulate in the recirculating solution. If the build-up of the excess substances is not too rapid, then it is quite realistic to pump the nutrient solution out of the installation before substances build up to adverse concentration levels.

Cooper (1979) suggested that the water supply should be tested for the following ions: nitrogen, phosphorus, potassium, calcium, magnesium, iron, manganese, boron, copper, molybdenum, zinc, sodium, chlorides and sulphate. The analysis should indicate which ion, or ions, might build up to adversely high concentrations.

Arrangements should then be made to conduct weekly analyses and to plot the build-up of the ion (or ions) on a graph as the concentration increases. In addition to the weekly analyses, close observation of the crop will indicate when changes begin to appear. This method, however, is very expensive.

Molyneux (1988) suggested a method for deciding when the nutrient solution should be discharged when hard water is used. This method was used successfully in Egypt when low-quality groundwater was used in the substrate system.

Molyneux suggested that the two most common salts that dissolve in hard water are calcium and magnesium. Electrical conductivity (EC) increases as soluble nutrient salts (not only calcium and magnesium) build up in the solution. In case of high EC, farmers should find out which ion is causing it and take the necessary corrective measures in the solution.

A conductivity meter is used to measure the base EC (EC refers to the calibrated EC value of the water source used before nutrients are added). Care must be taken to use a representative sample taken from a pond or other open water source. The sample should be collected from open water, not from puddle edges. If collecting a sample from the tap, the water should run for a minute before collecting the sample. If the conductivity factor (CF) meter is not temperature compensated, then the sample temperature should be adjusted to around 20 ºC before taking the reading (El-Behairy, 2015). For the purpose of nutrient solution management water can be divided into the following three categories (Molyneux, 1988):

- EC between 0 and 0.3 mmhos cm^{-1} or dS/m or ppm units for EC: follow fresh water instructions;
- EC between 0.4 and 0.8 mmhos cm^{-1}: follow hard water instructions;
- EC over 0.9 mmhos cm^{-1}: refer to special adaptations.

Special measures must be taken when managing a nutrient solution using hard water (Base EC '4-0.8 mmhos cm-1).

The effect of using hard water is that, after nutrients are added, up to a pre-established level, the changes in the EC of the solution will not only reflect the removal of nutrients from the solution by the plants, but also the remaining salts from the hard water that have not been used by the plants. When hard water is used between 0.4 to 0.8 m mohs, approximately half of the salt will be absorbed by the plant and the other half will remain in the tank. This will increase the EC of the nutrient solution. This means that half of the nutrients dissolved in the solution are not available for absorption by the plants. This has to be taken into consideration, when adjusting the nutrient solution. When adjusting the nutrient solution, the value of the EC as a result of the salts remaining in the solution should be added to the reading of the EC meter to ensure that the nutrient solution will be able to release the required elements needed by the plant.

The base EC should then gradually be increased to compensate for the gradual decline of the nutrient status of the solution. When the base EC reaches an unacceptable level, the solution must be discarded and replaced with a new solution. The following procedure demonstrates how this is done.

Regarding the composition of the nutrient solution, plants require 16 essential elements for growth and development. Without these nutrients, plants cannot complete their life cycle. No other elements can replace the role of these nutrients in plant growth. These 16 elements include micro and macroelements, as shown below.

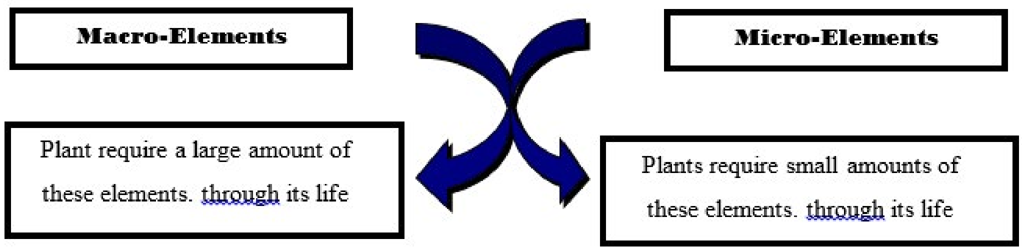


Figure 3.33 Macro and micro-elements

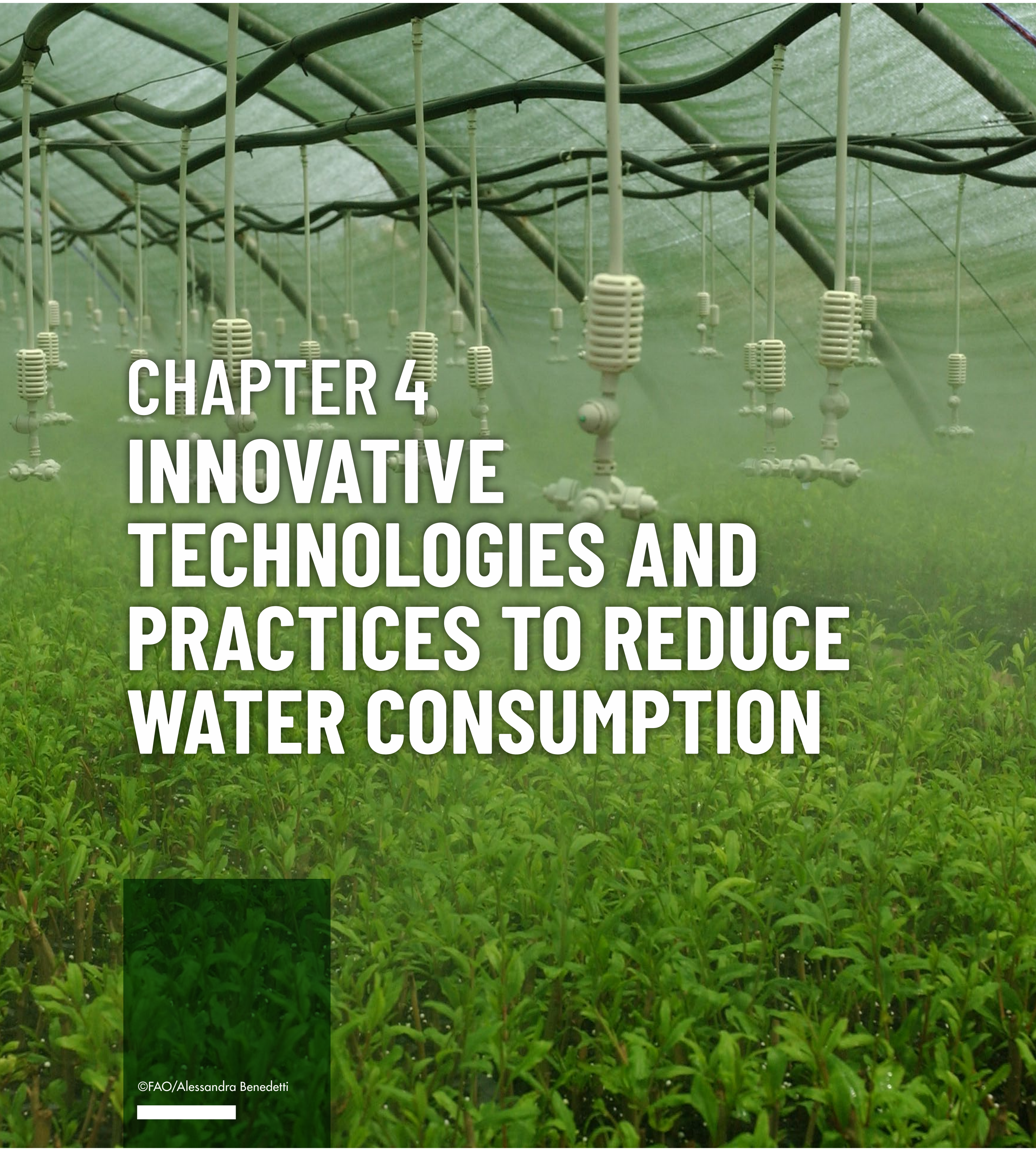
Source: *El-Behairy, 2015.*

All the nutrient elements required for plant growth must be present in the nutrient solution in soilless culture systems. Some of the elements may be present in adequate quantities in the water supply, while others must be added to the water. These usually are nitrogen, phosphorus, potassium, calcium, magnesium, iron, manganese, boron, copper, zinc and molybdenum. The following table provides an example of ideal concentrations (ppm) of elements in a nutrient solution for tomato production.

Table 3.2 Standard reference concentration (ppm) of elements in nutrient solution for tomato production

Element	Symbol	Concentration
Nitrogen	N	200
Phosphorus	P	60
Potassium	K	300-350
Calcium	Ca	170
Magnesium	Mg	50
Iron	Fe	3-6
Manganese	Mn	0.5-1.0
Boron	B	0.3
Copper	Cu	0.1
Molybdenum	Mo	0.2
Zinc	Zn	0.05

Source: *Cooper, 1979.*



CHAPTER 4 INNOVATIVE TECHNOLOGIES AND PRACTICES TO REDUCE WATER CONSUMPTION

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CHAPTER 4
INNOVATIVE TECHNOLOGIES AND PRACTICES TO REDUCE WATER CONSUMPTION

4.1 INTRODUCTION

Increasingly, global water resources are becoming limited because of rising water demands in agriculture, households and industry. Dramatic water shortages have recently been reported in California and areas around the Brazilian megacities. On the supply side, climate change is causing irregular rainfall and increasing dehydration of the land, combined with high nutrient loss, with extreme negative impacts for agro-industry.

The discussion on solutions centres mainly on increased water efficiency in agriculture, with the associated constraints of lower levels of production or growing less profitable alternative crops. Another focus centres on alternative sources of water, mainly focusing on desalination of seawater using large thermal-driven, multi-flash desalination units around power stations and on the technology of reverse osmosis.

A mostly overlooked solution relates to a still relatively small area of research on new greenhouse technologies. As agriculture is the largest consumer of fresh water, consuming about 70 percent of global freshwater, the general aim is to economize water demand through evapo-condensation strategies. What if water consumption can be minimized to zero by cycling water between crops, humid air and condensed water? Minimizing water loss to zero should be possible within greenhouses. The technical feasibility of zero water consumption in greenhouses has been demonstrated. However, commercial applications are not yet on the way, mainly because existing concepts are not sufficiently viable. If it is possible to recycle irrigation water from air humidity, a principle solution for agriculture becomes realistic. Furthermore, water consumed by other sectors, such as households and industry, can be recycled for crop irrigation.

Another source of water is treated waste water, which can be used for irrigation and/or evaporative cooling as well as for renewable material production, depending on the quality of the water. Saline water can be integrated into the water-saving and recovery technology, resulting in greenhouses producing more freshwater than they consume. This would transform crop cultivation from the largest water consumer into a producer of water.

Water recycling requires the creation of high values of air humidity, which can be achieved within greenhouses. The second step of water recycling is the condensation process, which can only be achieved at temperatures below air temperature. Thus, water condensation requires a cooling mechanism, or the greenhouse temperature must be higher than the temperature of the surrounding air.

There are two main methods of water capture in protected cultivation. One is capturing water from the outgoing air in an open greenhouse, and the other is to capture water from an internal air cycle in a closed greenhouse. Each system uses particular concepts for water capture, and both are relevant. Both strategies have similar goals:

- Energy efficiency of cooling/ condensation and air exchange: The energy requirements of the greenhouse system must be lower than the energy demand for state of the art greenhouse systems plus state of the art water desalination systems.
- Cost efficiency of the needed infrastructure (cooling devices, heat exchangers, thermal storage): Investment and supply costs of water cycling greenhouses must be lower than those of state of the art agricultural methods, plus the costs for conventional water supply (here desalination) and the costs for water transport.

Though there are principle solutions, none of the concepts has yet achieved these goals of energy and cost efficiency. Solutions for increased energy efficiency and economics have to be improved, essentially in the following areas, in order to establish market-ready greenhouse systems with integrated water cycling:

- methods for improved temperature differences between hot/humid air and available sources of cooling;
- methods of heat transfer between hot/ humid air and sources of cooling;
- methods of storing heat (from day to night) and cool (from night to day).

These tasks are mainly related to energy engineering. Once solutions are sufficiently developed, further tasks in the areas of water technology, horticultural practice and construction engineering will have to be dealt with to provide final integrated solutions for improved productivity, cost efficiency and sustainable self-replication of the solution.

4.2 METHODS FOR IMPROVED TEMPERATURE DIFFERENCES BETWEEN HOT/HUMID AIR AND AVAILABLE SOURCES OF COOLING

When condensing water vapour from the air, either air humidity has to be increased to the saturation point, or air temperature has to be reduced, or both at the same time. Water evaporation also is a source of cooling, so both forces work closely together. Once air humidity is at 100 percent relative humidity, no further increase is possible. If the temperature of saturated air goes down, condensed water appears and can be collected. Besides cooling the air, methods to increase the temperature and humidity in a greenhouse contribute to condensation, as the definition of cool in the context of condensation is related to ambient temperature. For example, ambient air temperatures of 35 °C can be considered cool, if greenhouse temperatures are 45 °C and humidity rates are high.

4.2.1 EVAPORATIVE COOLING

Evaporation is the main source of cooling in a greenhouse. A standard greenhouse is primarily cooled by incoming dry air, plus the evaporative cooling of the plants and the removal of humid air. In many cases, greenhouse temperatures are below ambient temperatures because of this effect, even with high solar radiation input. Evaporation of water not only has a powerful cooling effect but also facilitates the condensation process. As air humidity rises, less cooling power is needed to force condensation.

Compared to evaporative cooling, the effect of a cool fresh air supply and removal of hot air is much less effective, especially in hot and dry areas. A large leaf area, a well-developed canopy, tropical crops and permanent cultivation of crops of different ages and sizes are methods to improve the natural potential of evaporative cooling provided by vegetation.

Additional methods of boosting evaporation use wet pads and fog/mist systems. These contribute to cooling but may have negative effects, as they consume freshwater and increase the level of relative humidity in a way that reduces the natural evaporation of the plants. (Saline water can be used on wet pads to minimize the use of fresh water, but further development is required, including research on alternative pad materials, water dissipation systems and methods for water pre-treatment – especially for removal of calcium ions, which are soluble only in water and, thus, clog pads and spray nozzles.)

The negative impact of humid air is related to the internal cooling methods of the crops. The internal temperature of a leaf can be up to 10 ºC to15 ºC lower than the temperature of the surrounding air. This is the result of water evaporation from the wet surface of the cell parenchyma, which has a considerable expanded surface of three-dimensional nature. By opening the stomata, saturated air escapes, while less humid fresh air enters. If the incoming air is already very humid, the cooling effect will be lower.

Additional evaporation from evaporation pads can also have a positive effect if there is not enough water available for the plant, for example when the roots of the plant are insufficiently developed. This is especially the case with young crops in nursery greenhouses. As the uptake (enrichment) of humidity (moisture) in air grows exponentially with the temperature, also well-developed plants may have stress with high temperature conditions associated with very dry air. In such case, even if enough water is available in the soil or substrate, plants may not be able to absorb enough water through the roots and stems to compensate for the hight rate of transpiration.

It is apparent, then, that there are no fixed optimum climate conditions for plant growth, but rather, that optimum conditions vary in relation to a set of climate factors, including radiation, temperature, humidity and CO_2 concentration. Measures for creating the best conditions for crop growth at high temperatures have not yet been fully developed, as it is not easy to manage all the relevant parameters. Nevertheless, there are new and better ways to control the climate inside greenhouses. Some of these are described below.

4.2.2 HEAT PUMPS

The most common and established means of cooling to drive the condensation process is the use of heat pumps. A large number of closed-system greenhouses are equipped with mechanical cooling mechanisms. These were built primarily for experimental reasons to provide specific conditions for horticultural testing, and the system was never considered a serious approach for producing or recycling water on a large scale, as it consumes a great deal of energy. Besides cooling the air to below the dew point, all the latent energy that is converted into sensible heat along the phase change from vapour to liquid water has to be provided. This is 680 kWh/m^3, which is the physical coefficient for phase change of water.

The disadvantage of using absorption heat pumps (driven by thermal rather than mechanical energy) is that they require relatively high regeneration temperatures. Even if a cheap thermal energy source is available, these systems still require back-cooling of the heat removed from the greenhouse plus the heat provided for the absorption cooling machine (in a relation of about 1:1). This back-cooling requires either water again for evaporative cooling or a lot of ventilator power, for dry cooling.

In sum, today's heat pump systems can only be used in niche applications and are not capable of large-scale greenhouse water condensation. The combination of state of the art desalination and standard greenhouse practices will always be more energy efficient and cheaper. That is why research must focus on unconventional sources of cooling.

4.2.3 PASSIVE COOLING: STORING COOLER NIGHT TEMPERATURES FOR DAYTIME USE

If thermal storage is used to accumulate coolness during the night, this coolness can be used for condensation processes. This is one of the main methods used in new generation greenhouses (NGGHs).

4.2.4 DEEP OCEAN WATER

Deep ocean water has been cited as a possible source of cold water for cooling greenhouses. It also can be integrated into water recycling greenhouses, especially as described in the NGGH integrated concepts later in this text. (See section 4.6.1.3. "Fan and pad with second, heated evaporator and cooled condenser".) Local conditions that could meet the cooling water temperatures for this principle can be found on the Canary Islands and in the Caribbean.

It should be noted that huge portions of thermal energy must be managed in greenhouses, with solar loads of 0.5 to 1 kW/m^2. Cooling with cool water requires 50 litres per m^2/hour of water with a temperature difference of 20 K to cool one square meter. Considering 10 hours of cooling operation, the amount of water needed amounts to 0.5 m^3/day. The energy required to pump the water will be enormous, especially if the greenhouses are not located directly on the seashore. A further restriction is the availability of cool ocean water. In many coastal areas, ocean water is relatively warm, even at relatively high depths. This is especially the case in the Gulf countries. Finally, discharging huge quantities of heated water into the sea can also cause environmental damage. Furthermore, the high cost of coastal land should be considered as well. For these reasons, the feasibility of this approach is limited.

4.2.5 GROUNDWATER

The use of groundwater for cooling purposes is only possible when the velocity of the groundwater flow is very high, as continuous heating of stationary groundwater will finally result in overheating. In this case, it will need active re-cooling during the night-time. The characteristic then would be similar to thermal storage as described in section 1.3. It would only be feasible at a short distance from the surface. Also, the average outside temperature would have to be well below the desired temperatures for good crop growth (around 15 K).

4.2.6 TEMPERATURE DIFFERENCE BETWEEN AMBIENT AIR LAYERS

The concept of open slope greenhouses built from the bottom to the top of a mountain includes the concept of air ventilation caused by rising warm air. By implementing evaporative cooling, hot and humid air reaches the top of the mountain and is cooled by the surrounding air, which is generally cooler than the air at the ground level. In case the surrounding air is colder than the air inside the greenhouse, there will also be some condensation on the cover.

More condensation can be achieved by adding an air-to-air heat exchanger at the greenhouse air outlet, using the temperature difference between inside and outside air for water production.

4.2.7 CULTIVATION OF THERMOPHILE ORGANISMS

Thermophile, photosynthetic organisms can contribute to improved condensation, as temperatures in greenhouses can rise sufficiently high against outside temperatures to allow condensation along the greenhouse walls or along extended air-to-air heat exchangers. Growers can "zone" the greenhouses, placing crops with different heat tolerance levels in different zones, connected by an air cycle (in a closed greenhouse) or by linear air flow (in an open greenhouse) with a condensation heat exchanger at the point of peak temperature. Breeding of heat-tolerant crops that are not drought-resistant may be possible with water condensing greenhouses. Currently, this is not a goal in agriculture.

4.2.8 CO_2 ENRICHMENT

In a closed greenhouse, the concentration of CO_2 can be accelerated to high values, without losing CO_2 via air outlets. This allows higher rates of photosynthesis but also increases the optimum growth temperatures because the leaves have greater amounts of CO_2, which increases their photosynthetic performance, even during phases of decreased stomata opening.

This may contribute to higher differences between the greenhouse air temperature and the potential source of coolness. This is also interesting, as total humidity uptake of air grows exponentially with increased temperatures, thus allowing higher rates of condensation, compared to cooling processes at lower temperature levels but with similar temperature differences (similar delta T) between the air and the cooling source. Economical and efficient accumulation of CO_2 in this context is an advantage of closed greenhouses over open (water condensing) greenhouses.

4.2.9 EVAPORATIVE COOLING + AIR DESICCATION

In desiccant cooling, the air is dried in order to increase the capacity of evaporative cooling. In open greenhouses, air desiccation can be carried out at the greenhouse air inlet, in front of wet pad evaporators or as a stand-alone application to increase the evaporation rates of the crops and increase the cooling capacity. However, the process of dehumidifying air produces heat, which must be removed before the air enters the greenhouse. This can be done using heat exchangers that transport the heat to ambient air or by using a liquid desiccant.

In a closed greenhouse, desiccants can be used for the uptake of all humidity derived from evapotranspiration or humidifiers. Then, during regeneration, the humidity can be directed back to the air and from there condensed for water capture and related heat release.

4.3 METHODS OF HEAT TRANSFER BETWEEN HOT/ HUMID AIR AND AVAILABLE SOURCES OF COOLNESS

As heat transfer is the main process related to condensation, heat exchange hardware is one of the crucial cost factors of NGGH. Standard equipment, such as that used to build air conditioners may be suitable but can be expensive or affected by high-pressure drops with related high energy costs for ventilation. As with the cooling process itself, heat exchange equipment may greatly impact the performance and final costs of a NGGH and the right choice may be crucial for the final viability of a greenhouse concept.

4.3.1 AIR-TO-AIR HEAT EXCHANGERS

Air-to-air heat exchangers are needed for direct heat transfer between the greenhouse and the outside environment. This process is not very important in open greenhouses, but in a closed greenhouse, all the energy that enters the greenhouse has to be ejected back to the surrounding air through a heat exchanger. The most evident example is the greenhouse cover, which constantly transfers heat when the inside and outside temperatures are different. Additional air-to-air heat exchangers usually have plastic- or metal-plated heat exchangers that work in cross-flow or counter-flow mode. Ventilation is needed to move the air through the gaps between the plates. Additional ventilation may also be needed for the outside, requiring energy for both air streams.

Efficient heat transfer also requires some turbulence on the surface, which may also require further ventilation power, especially during periods without wind. Thus, this technology involves costs for the exchangers and ventilation equipment and related energy costs.

4.3.2 AIR-TO-LIQUID HEAT EXCHANGERS

In this system, an air-to-liquid heat exchanger is used to transfer thermal energy from the greenhouse air to a liquid cooling medium. The cooling medium may be an external source of coolness (cool from a heat pump or deep ocean water, for example) or it may be provided from an internal thermal storage, with delayed heat release, especially during the night-time.

Usually, heat transfer between two liquids is more efficient than between a liquid and air.However, if condensation is involved in the process, heat transfer at the air side is again significantly increased due to the wet exchange surface and due to the released phase change energy.This means that, optimally, the air supply to the heat exchanger should be very humid, so that the condensation process appears on a large part of the surface, while only a small surface is needed to cool down the air to the dew point. In case the transpiration of the crop is limited, the efficiency of heat exchangers might be increased by misting or wetting the soil surface. However, the optimum humidity for crop growth will always present limitations.

4.3.3 SURFACE vs HEAT CONDUCTIVITY

As to the materials used, cheap plastic surfaces provide lower heat conductivity but can still be cost-effective if built with larger surface areas. The non-corrosive properties of plastic can be an advantage providing long-term stability of the component. For heat removal through the greenhouse cover, the northern wall of a greenhouse can be used for increased heat release, as a larger surface can be implemented (for example, by installing the plastic foil in a zigzag shape). Metallic materials can be installed on the north wall, as there is not much radiation loss on that side if non-transparent material is used.

4.3.4 DIRECT CONTACT AIR-TO-WATER HEAT EXCHANGERS

A direct contact air-to-water heat exchanger can provide a large exchange surface without the need for pipe bundles. In this type of exchanger, the cooling water is in direct contact with the air, and water vapour from the air condenses directly into the cooling water. The disadvantage is that if the same installation is used to withdraw heat, for example for day/night heat storage, the water evaporates again and has to be re-condensed on another surface, such as the greenhouse cover. The heat exchange surface can be built just by the drops or by a matrix that is covered with a water film or multiple water streams. The exchange surface between liquid and air is only provided for a very short time when using falling drops only, like in a shower. For this reason, the water has to be pumped continuously, requiring a great deal of power.

A surface structure (called "packing material") can keep the water on the contact surface for several seconds or up to several minutes, depending on the flow speed. Direct contact heat exchangers have been successfully tested in closed greenhouses.

4.3.5 DIRECT CONTACT AIR-TO-LIQUID DESICCANT HEAT EXCHANGERS

Instead of water, liquid desiccants, such as strong solutions of water and magnesium chloride or calcium chloride, can be used as a thermal transport medium. The main difference between these solutions and water is the lower relative humidity of the air needed to force a mass transfer of water vapour from the air into the liquid. Dehumidification of air can already be performed at between 10 and 99 percent relative humidity, depending on the concentration of the salts and the specific properties of the salt. The phase change of water always releases heat, and by the nature of the desiccant properties, the gained heat uptake is higher than the air temperature. When forcing water to condense, the temperature will remain below the air temperature – a disadvantage since less energy is taken out of the system. Once the water is in the desiccant, there is no direct yield of condensed water. The water has to be desalinated in a second stage (usually during the night) and the heat released from the storage medium.

4.4 METHODS OF STORING HEAT AND COOLNESS DURING THE DAY AND NIGHT

4.4.1 WATER

Water has a heat capacity storage of 4.3 kJ/ (kg K), much higher than other substances such as iron or concrete. Another advantage of water is that it is very cheap. Efficient energy accumulation aims to reach a high-temperature difference between the loading and unloading phases.

4.4.2 SOIL

Wet soil, with sufficient particles of clay and/or organic material, has a very good heat capacity (almost as good as water), while pure sand has a relatively poor heat capacity due to its high air content and insufficient water-holding capacity. The particle density and water content of the soil also contribute to good heat conductivity, allowing sufficient quantities of the thermal load distribution to a larger total volume. The disadvantage of soil is that the ground surface usually limits the exchange surface to the greenhouse air. If using container crops, the surface can be increased by the added container surface. However, the available soil volume and the container volume together is insufficient to store the heat from the solar radiation on the greenhouse surface, especially in hot climates. Additional storage volume can be built up with heat exchanger pipes placed in the ground, transferring the heat to external water storage. Here also the uptake of heat is limited by the limited heat transfer from the soil surface and from the soil through the pipes. Heat exchanger pipes also have relatively high costs, as additional materials and additional ground excavation are needed.

4.4.3 GRAVEL, SAND AND WATER

If using sand or gravel, the heat capacity can be improved by filling the volume with water. This requires an additional waterproof cover but has the advantages of additional heat capacity in the ground area. Furthermore, improved heat conductivity is provided from the surface into the storage material. The area can also be loaded by pumping the water to a heat exchanger.

4.4.4 SUBSTRATE PLUS SOIL

Artificial substrate cultures can serve as additional storage material. If the soil is not used as a substrate, it can be heated up, even beyond the heat tolerance of the crops. If the substrate is located at a certain distance from the soil, it can act as additional (passive) means of day/night temperature equalization. Substrates with higher content of organic material, such as compost or charcoal, contribute to higher water content and, thus, higher thermal capacity.

4.4.5 LIQUID DESICCANTS

Liquid desiccants can be used as thermal and thermo-chemical storage material by making use of temperature and salinity differences. As an added advantage over solid desiccants (such as silica gel), liquid desiccants can also be used as a transport medium, as they can be pumped to a different place (for example, to a central storage container within a greenhouse farm). As a storage medium, they have the advantage that no heat exchanger is needed to transfer heat from the desiccant into the storage medium (water, soil, etc.). Desiccants have a slightly lower heat capacity compared to water, which is compensated by the higher density. One partially unsolved problem, however, is that desiccants are highly corrosive, especially if they contain chlorides.

4.4.6 PHASE CHANGE MATERIALS

Phase change materials (PCMs) are used as a storage medium due to their very high heat capacity, which is needed when dealing with solid-liquid phase changes. For example, the melting heat of ice is 332.8 kJ/kg, which is around eight times more than if the same amount of water is changed 10 degrees in temperature.

Different PCM materials provide cooling capacity at a specific temperature or specific range of temperatures. The goal for greenhouse cooling is to provide a sufficiently cool temperature below the target temperature during the daytime (by melting the PCM) and a sufficiently high melting point above the natural night-time temperature of the region to allow the passive regeneration of the PCM (through re-solidification). A liquid storage medium (water or liquid desiccants) can be combined with the PCM contained in macro capsules. Another option is to include the PCM microcapsules into the soil, the substrate or the construction material of a greenhouse. This practice will provide a passive cooling effect. Current research in NGGH seeks to identify and test affordable PCM materials that work in the range of phase change temperatures required for heat uptake from related greenhouse systems. Research must also be done on the interaction of different solid and liquid materials.

4.4.7 SOLAR PONDS

If desiccants with higher and lower densities are used, storage can also be designed as a solar pond. This works with highly concentrated material on the bottom and less concentrated material on top. The solution requires sufficient cold temperatures for heat release during the night-time, as additional external heat is added to the heat storage. However, this is also an option for locations where greenhouses need heating, rather than cooling, or both cooling during the daytime and heating during the night-time. Due to the difference of the densities, solar radiation reaching the bottom of the storage pond heats up the concentrated material that is not rising to the surface, as the low concentrated material acts as a barrier. In this way, the temperature can rise to 70 to 80 ºC .Thus, the solar pond acts as a combination thermal storage and solar collector.

4.5 TRANSPORT OF AIR AND STORAGE MEDIUM

One element that significantly impacts the cost of NGGH is the energy consumption required to transport greenhouse air and thermal storage fluid. Normally, this is achieved by using ventilators and pumps. Air ventilation can be minimized by minimizing the pressure drop of related heat transfer units and by decentralizing heat transfer units placed in the greenhouse. Another approach is related to buoyancy-driven air ventilation: using the different densities of hot and cold air and related processes of rising and falling air layers, caused by the heat exchange processes implemented. State-of-the-art heat exchangers usually require a certain pressure drop to work at maximum performance. New heat exchangers must be developed that allow passing air to rise solely because of their rising temperature or to fall as they cool, at sufficient speed and volume flow.

Another issue is that the pumps have to be of very high quality in order to withstand corrosive media. The development of low-cost pumps that can be used with corrosive media is a specific research topic. This is, however, a minor point compared to the issues mentioned above.

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CHAPTER 5
THE NEW GENERATION OF GREENHOUSES

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CHAPTER 5
THE NEW GENERATION OF GREENHOUSES

5.1 NEW GENERATION GREENHOUSES (NGGH): OVERVIEW OF TECHNOLOGIES

5.1.1 OPEN GREENHOUSES

FAN AND PAD WITH A CONDENSER

As an addition to the state of the art technology of fan and pad greenhouses, a condenser (for instance, an air-to-liquid heat exchanger) is added in front of the air outlet of the greenhouse. Air coming into the greenhouse is pre-humidified for cooling purposes and the vegetation in the greenhouse further increases the humidity and the total water content of the air. By providing a cool surface, water is condensed from the air before leaving the greenhouse. This requires coolness, which can be provided by a heat pump, by deep ocean water or using a storage medium. This is only possible if the incoming air is very dry, as part of the enthalpy goes back to the greenhouse rather than being ejected out of the greenhouse. Otherwise, the cooling effect is reduced, and the humidity in the greenhouse is excessive.

As an alternative source of coolness, the condenser can also be an air-to-air heat exchanger, if the coolness comes from the ambient air. This method is only possible at a strong increase in temperature within the greenhouse, which in most cases exceeds the optimal temperatures for healthy growth of the plants. This concept is known as "seawater greenhouse" and has been established in several prototypes in Oman, Portugal and Spain.

Benefits:

- The concept is very simple and can be added to existing fan and pad systems.
- It reduces fresh water consumption, freeing up fresh water for crop irrigation.

Limitations:

- The system only works with low outside humidity (< 40 percent) and high radiation.
- The system still loses a lot of water, as only a small portion of the water is recycled.
- The system is only as good as the source of coolness. If the evaporation pad at the air entry is used as a source of coolness to run the condensation, then the solution is technically simple. However, the cooling performance is weak and not suitable for hot climates and not at all suitable for humid climates.

Figure 5.1 shows the principle of a condenser used to recycle water from the open-air stream out of the greenhouse. Coolness is provided from the evaporation pad at the air inlet, which potentially can be fed with seawater. Gained sweet water then can be used for irrigation.

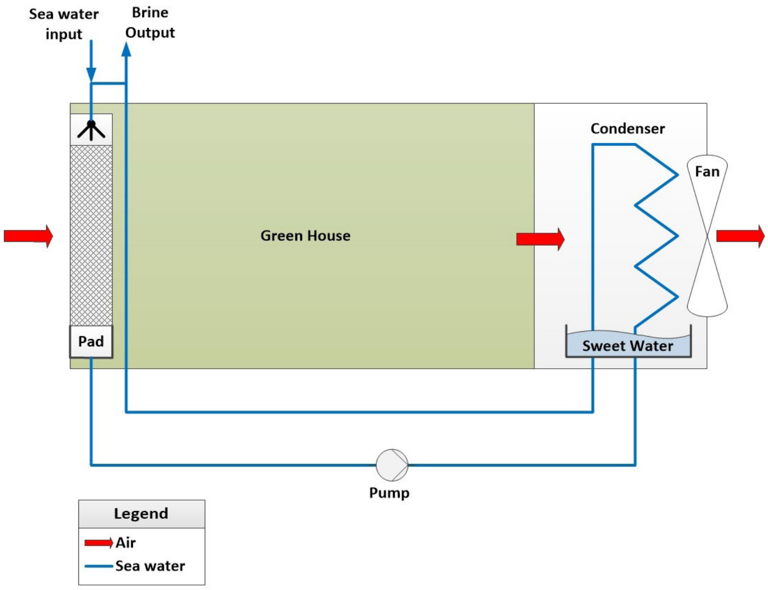

Figure 5.1 Condenser diagram

Source: *Watergy GmbH, 2020.*

FAN AND PAD WITH ADDITIONAL, EXTERNAL EVAPORATOR AND CONDENSER

An additional evaporator outside the greenhouse can be used in the configuration above as a possible source of coolness. This method is not at all water efficient, as only a portion of the water from the greenhouse internal evaporation pad is recycled, while water from the external pad is lost. However, this can be a realistic system if the evaporation pads are fed with seawater (at sufficient proximity to the coast). A major disadvantage, however, is a very high rate of brine released back into the sea or a high rate of salt output in systems, with a total reduction of water from the feed source.

Benefits:

- An additional evaporative cooler is a strong source of coolness.

Limitations:

- The system does not work when the outside humidity is high.
- Regarding water savings, the system only makes sense if seawater is used in the evaporation elements. The supply of seawater and brine recharge must fit the economic framework.
- Seawater evaporators are not available on the market. They are a part of NGGH technology that needs further research to solve problems of pad clogging.

Figure 5.2 illustrates an improved version of the open fan and pad greenhouse along with an external cooling tower, providing cooling for the collection of condensed water. This operation is only feasible with seawater as a source of evaporative cooling, as huge amounts of water will be consumed.

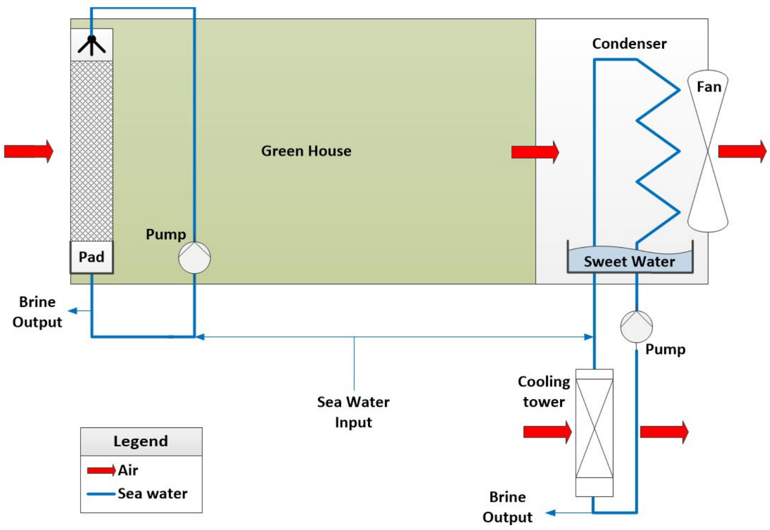

Figure 5.2 Improved version of the open fan and pad greenhouse

Source: *Watergy GmbH, 2020.*

FAN AND PAD WITH SECOND, HEATED EVAPORATOR AND COOLED CONDENSER

Instead of providing an external source of coolness, as in the previous method, a further option is to increase the temperature and humidity at the air outlet with a second evaporator and to cool back the air in the direction of ambient temperature by using an air-to-air heat exchanger. Heated water or seawater can be provided from external sources of residual heat, such as a power station. Other potential means of heating are solar thermal collectors or solar ponds. This system can also help if a day/night thermal storage is used, but the cooling power is still insufficient to reach the dew point temperature at the condenser.

Benefits:

- With sufficient temperature levels at the second humidifier, the system can use ambient air for cooling. Generally, heat is more accessible than coolness.
- The system can be used in combination with solar ponds as a source of heat for the desalination process and a source of coolness for the surrounding area of the greenhouse.
- The system could be advantageous if using deep seawater for cooling and residual heat from a solar thermal power station for additional heat supply.

Limitations:

- If no source of residual heat is available, the costs for heating (especially solar heat) may be too high for this application. The system does not dry the incoming air. Thus, when ambient humidity is high, the cooling at the entrance will be weak, and greenhouse humidity rates may be critically high.

When cooling is insufficient, an additional heated evaporator can be placed in front of the condenser to get the air closer to the dew point and to increase the condensed water yield (Figure 5.3).

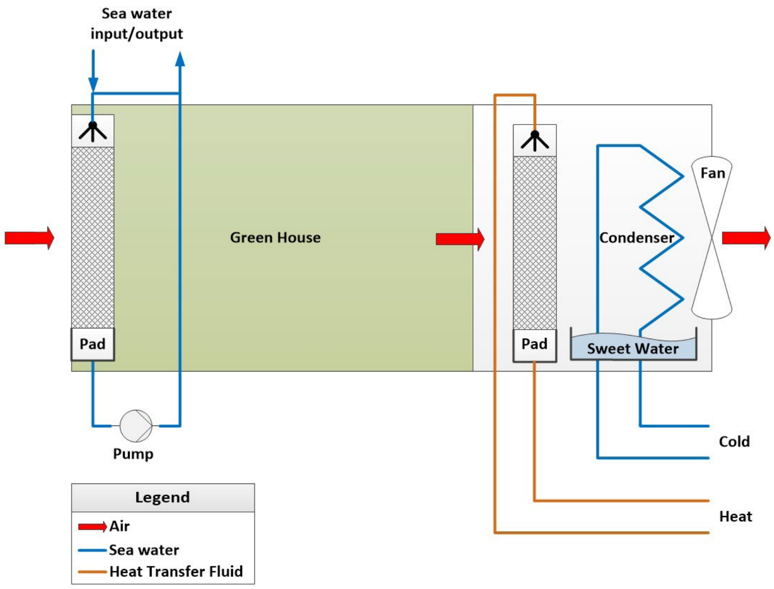

Figure 5.3 Diagram with additional heated evaporator

Source: *Watergy GmbH, 2020.*

FAN AND PAD SYSTEM WITH CONDENSER AND DESICCANT WHEEL AIR DRYER

In many regions, ambient air is already too humid for a pad system to cool the greenhouses efficiently. In such conditions, fan and pad systems provide insufficient temperature reduction and leave excessive humidity at the air inlet. These problems may be solved using desiccant wheel air dryers. The wheel includes a dry desiccant material. It absorbs humidity from the incoming air around one half of the wheel, while the turning wheel transfers the absorbed water to the outgoing air, which is in contact with the other half of the wheel. The outgoing air may require extra heating to provide a high enough temperature to regenerate the desiccant material.

The process for regenerating the desiccant material is the following: There is a heat exchanger wheel behind the desiccant wheel. This wheel takes up heat from the incoming air and provides part of the heat needed for the regeneration process at the outgoing air channel. As the wheel has lowered the air humidity at the inlet, an evaporation pad can then provide sufficient cooling performance. The cool air which is generated behind the condenser is also recycled back to the incoming air through the heat exchanger wheel. Between the wheel and the desiccant regenerator, a further heat source is required to reach the temperature required for desiccant regeneration.

Benefits:

- The water recycling system functions in regions with high humidity and does not require thermal storage.

Limitations:

- The system needs a large number of components, an additional heat source for desiccant regeneration, and a source of coolness to run the condenser. It seems to be too complex for a closed greenhouse system but offers a solution for open systems in cold and humid climates.

A state of the art solution from building technology that uses a desiccant wheel and a heat exchanger wheel makes open water recycling systems also suitable to hot/ humid climate conditions (Figure 5.4).

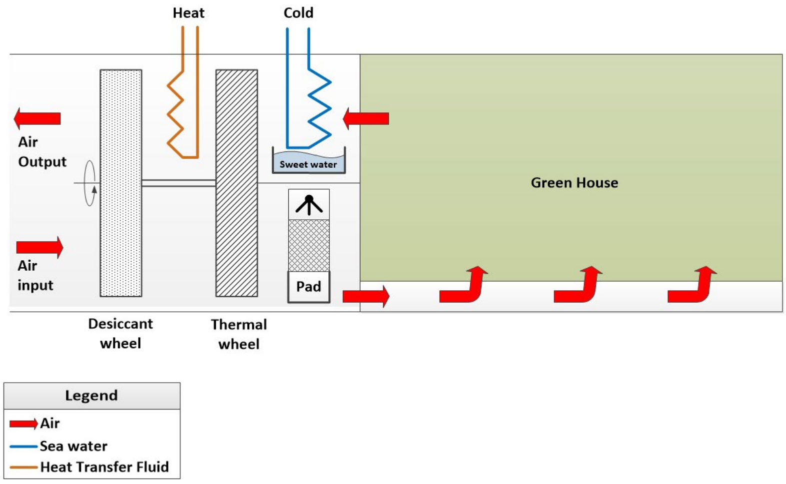

Figure 5.4 Using a desiccant wheel and a heat exchanger wheel

Source: *Watergy GmbH, 2020.*

5.1.2 PARTIALLY CLOSED GREENHOUSES

WATER RECYCLING IN A FAN AND PAD GREENHOUSE WITH DESICCANT STORAGE AND AIR-TO-LIQUID DESICCANT HEAT EXCHANGER

Instead of using a condenser heat exchanger, the water leaving the greenhouse can be recovered using an air-to-liquid desiccant heat exchanger at the air outlet of the greenhouse. In this way, the water is not condensed as freshwater but is absorbed into the desiccant fluid. The desiccant increases in temperature in this process, and heat and a diluted desiccant are accumulated in a storage unit. In this way, water loss is prevented and heat is accumulated to be used at night. During the night-time, the water can be evaporated out of the desiccant back to the air. As the air temperature is then lower, the water evaporates into the air with the help of the stored heat. With the greenhouse operating in closed mode, the air humidity will rise, and finally, the condensation will appear on the internal side of the greenhouse cover. This system is dependent on there being sufficient temperature differences between the stored heat and the ambient night temperature. If the stored heat is of insufficient temperature, an additional source of heat is needed to reach sufficient evaporation in order to provide a full 24-hour cycle with absorption in the daytime and combined evaporation and condensation at night.

Benefits:

- The advantage of the system is that a portion of the heat released during the absorption process is stored and re-used during the night, while heat released to the air stream is not rejected back into the greenhouse, thus reducing the increment of daytime temperature. This is a benefit for locations with high daytime temperatures.

Limitations:

- The system does not dry the incoming air; so, when ambient humidity is high, cooling at the entrance will be weak, and greenhouse humidity rates may be critically high.

A semi-closed system can be run in open mode during the daytime, where humid air is not condensed but absorbed into a desiccant fluid that takes up water and heat (Figure 5.5).

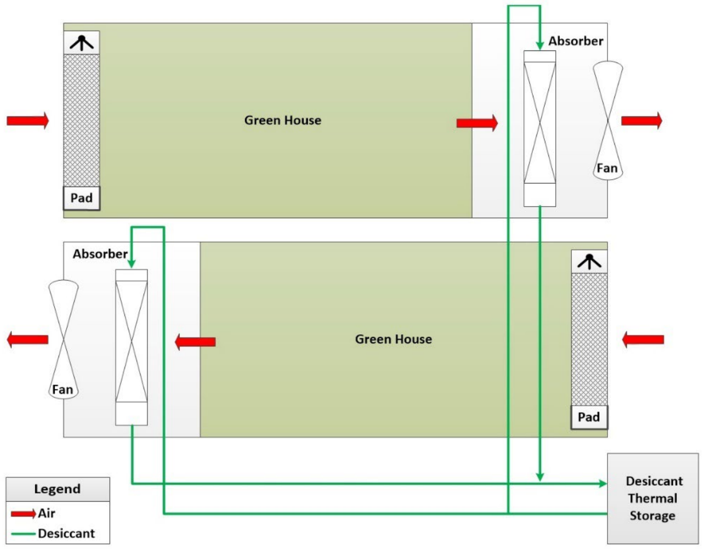

Figure 5.5 Semi-closed system – daytime

Source: *Watergy GmbH, 2020.*

During the night-time, the water in a semi-closed system is evaporated again into the greenhouse, which is then operating in the closed mode, and condensed water is collected on the inner surface of the greenhouse (Figure 5.6). Because the reduction of air humidity totally relies on the condensation at the greenhouse cover only, the humidity in the greenhouse will be very high throughout the night. Also, the air temperature will be high, because all the air is heated by the warm desiccant.

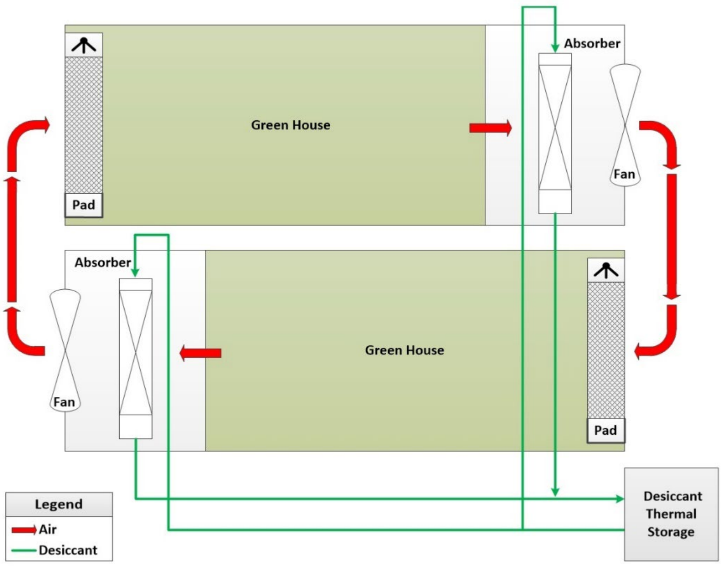

Figure 5.6 Semi-closed system – night-time

Source: *Watergy GmbH, 2020.*

5.1.3 CLOSED GREENHOUSES

A closed greenhouse may sound illogical, as it would not be possible to eject humid air as a means of energy reduction when that seems to be precisely what is necessary. However, if one considers the large amounts of water lost in open greenhouses, it is an important challenge to investigate the possibilities of closed systems, where practically no water is lost as almost all of it is captured within a cycle. Only humid air passing by possible leaks in the cover will be lost and will have to be replaced.

In humid climates, it is very complicated to first dry the ambient air and then re-humidify it for cooling purposes. Reducing the humidity and providing coolness to the air directly by reducing sensible heat is already very challenging. Reaching high rates of CO_2 and using only artificially-added CO_2 in a greenhouse, without losing it, is another challenge. This is of particular importance as high levels of CO_2 also make it possible to grow crops at increased temperature levels, thus requiring less cooling.

FAN AND CONDENSER WITH COOLNESS PROVIDED BY A HEAT PUMP

The most common closed system uses a heat pump to reduce the air temperature and remove latent heat, which is released during the phase change from vapour to water. Most laboratory scale closed environments use this system. It is also used in some Dutch projects using closed greenhouses, such as the Gesloten Kas system.

Benefits:

- The system is easy to control and relies on available technology. It is more feasible to obtain water from greenhouse air at the high rates of humidity reached by the closed system than any other "water from air" system.
- The system works irrespective of the outside humidity and temperature and can therefore be used in humid and warm coastal areas.
- The system works irrespective of the temperature and air humidity required for optimal crop growth, although it is obvious that the energy costs and investments grow substantially as the required target greenhouse climate temperature is lowered (say 15 °C) or target air humidity is further reduced (i.e. <75 percent).
- In cold regions, the closed greenhouse does not only capture water, but also heat, which can be used during the night.

Limitations:

- The main problem with this kind of system is the amount of energy required for cooling. The phase change alone requires around 350 to 400 kWh of electric energy to recycle one cubic meter of water. At a price of USD 0.10 /kWh, this would result in water costs of at least USD 40/m^3, which is certainly not competitive with other methods of water upgrading or desalination. Thus, the method can only be applied in research environments and cannot be used for commercial-scale production.

FAN AND CONDENSER WITH AN EXTERNAL COOLER

As in the open system described in Chapter 3, a closed system can potentially be cooled by an external evaporative cooler. This is only realistic if using seawater, for this purpose, as the goal of the whole system is to reduce sweet water consumption.

Benefits:

- This system has the advantage of having a closed growing environment combined with lower cooling costs. It is especially dependent on the availability of seawater and the costs of pumping large amounts of cooling water must be considered. Nevertheless, the need for pumping water is less than it would be if ocean water was used directly for cooling.

Limitations:

- The use of seawater on evaporation pads requires further research to resolve the clogging of the pads.

DAY/NIGHT STORAGE INTEGRATION

The most promising source of coolness is provided by the ambient night temperatures, which are usually lower than daytime temperatures. A day/night thermal storage unit is used to take up heat during the day, which can be released back into the greenhouse during the night to recharge the cooling capacity for the next day and to increase water evaporation and related condensation yields. Greenhouse cooling is provided by the vegetation's evaporation activity and by the cooling and dehumidification of the heat exchanger.

Additionally, a major portion of the heat is withdrawn through the outer surface of the greenhouse and is stored in the soil, which also provides a means of diurnal passive thermal storage.

This system has been used at the Watergy greenhouse in Almeria, Spain.

Benefits:

- The system provides a very simple method of air conditioning, allowing closed greenhouse operation using only primary energy for pumping and air circulation.

Limitations:

- The lowest night-time temperatures limit the cooling and air de-humidification function.
- The temperature in the greenhouse necessarily varies greatly between daytime and night-time.
- The diurnal average temperature inside the greenhouse cannot be lower than the diurnal average outside temperature. It will always be 5 to 10 °C higher. In the Gulf region, during the summer, the average temperature inside the greenhouse will be around 40 °C.
- The system still requires relatively high investment costs for an air-to-liquid heat exchanger used as the interface between air and storage.

The Watergy greenhouse in Almeria was the first closed greenhouse, cooled only passively by day/night thermal storage (Figure 5.7).

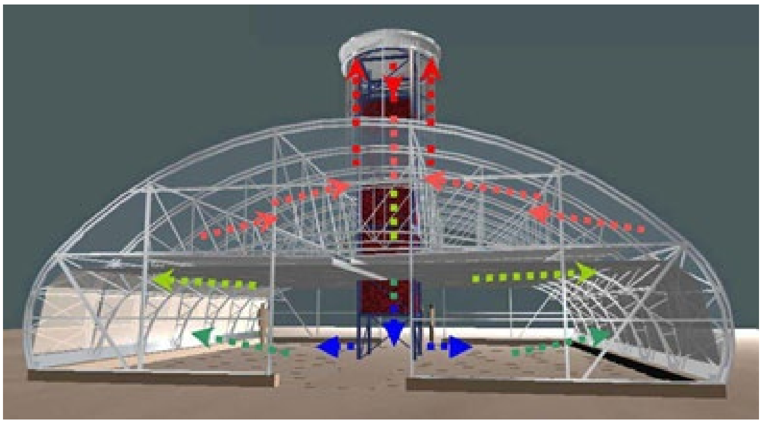

Figure 5.7 The Watergy greenhouse in Almeria

Source: *Technische Universität Berlin, 2003.*

DESICCANT GREENHOUSE

Considering the limits of closed greenhouses powered by day/night thermal storage, the desiccant greenhouse is seen as a more sophisticated and cheaper solution.

The first advantage is the air dehumidification function of the desiccant. Water vapour is actively removed from the air. Thus, it is not necessary to reach dew point temperature to force the phase change from vapour to water. In this way, the humidity reduction can be provided at much higher temperatures, which can be reached more easily using passive sources of coolness.

A second approach is to reduce the costs of air to liquid desiccant heat exchangers by building a simple model, for example, using locally available filling material. This only requires a surface structure to provide contact between the desiccant fluid falling along the surface and the air, which is blown through the surface structure. There is no need for steel or copper pipe bundles. Furthermore, heat transfer is more efficient in direct contact with the fluids.

The phase change heat is mainly converted to sensible heat, to load the storage unit, which can be transported into the storage unit by the desiccant flow. This is also a major difference from solid desiccants, as described in the desiccant wheel section, which do not provide the option of day/night shifting of heat.

For regeneration during the night-time, the flow is reversed, and the heated desiccant allows water to re-evaporate into the greenhouse air, which then condenses on the inner surface of the greenhouse.

The Watergy group has built the first prototype of a desiccant greenhouse in Cairo, Egypt. It is still under examination.

Benefits:

- The ambient air can provide cooling for condensation during the night only.
- Primary energy is only needed for air exchange and desiccant pumping between the storage and the heat exchanger.

- The costs of the materials and the heat exchanger are sufficiently low.
- The system functions independently of humidity rates of the ambient air, which makes it a favourite solution for hot/humid climates, like that of the Gulf region.
- The system can be used for a 9-month growing period.

Limitations:

- Desiccant regeneration is powered by the heat stored during a daytime cycle, but the functioning is also dependent on the night-time temperature, which must be sufficiently low to provide air with low water content as input for the regeneration process. If night-time temperatures are too high, this can be compensated by further heating the desiccant with external sources like solar heat or residual heat from other processes. This requires additional equipment such as solar collectors or a source of residual heat, such as a power station or air conditioning units within the same area. What is needed is a certain amplitude between a heat source and a source of coolness. Missing coolness can be compensated by heat.
- Another important limitation is the fact that, as in the case of the Watergy principle, the average diurnal temperature inside the greenhouse will always be notably higher than the diurnal average temperature outside the greenhouse. This means that, in the Gulf region, the average temperature in the greenhouse during the summer will be around 40°C.
- Another limitation is that the desiccant needs to be regenerated during the night. Beside daytime evaporation activities of the vegetation, night-time regeneration activity also contributes to high air humidity. Thus, the greenhouse air will always be humid.

A desiccant closed greenhouse captures humidity from the air constantly with minimal cooling demand (Figure 5.8). The closed system operates independently of ambient humidity rates, and thus can be used in the Gulf region. Water is condensed during the night on the inner surface of the greenhouse, powered by the heat from the desiccant storage collected during the daytime.

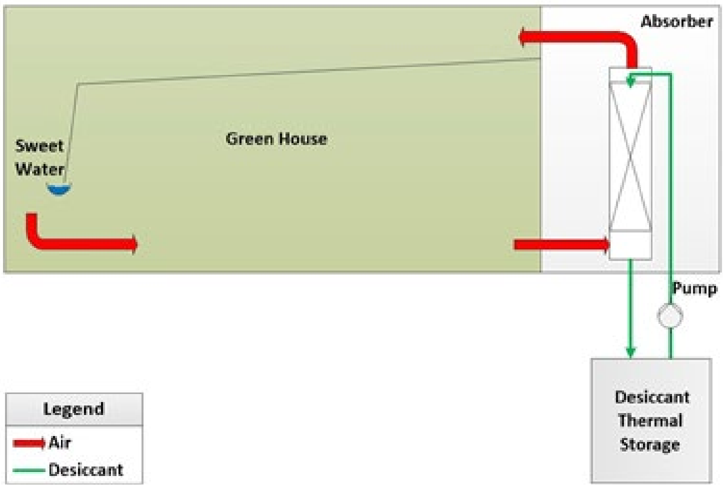

Figure 5.8 A desiccant closed greenhouse

Source: *Watergy GmbH, 2020.*

CLOSED GREENHOUSE WITH IMPROVED AIR-TO-AIR HEAT REMOVAL

In conditions of higher night-time temperatures and especially with the input of external heat, a larger surface to release heat from the greenhouse into the ambient air is required. This can be achieved by increasing the surface of the greenhouse or by providing a standard air-to-air plate heat exchanger with internal greenhouse air ventilated against a wall in contact with ambient air flow.

This system has been built by FAO, in cooperation with the Watergy Group, in Al Dhaid, United Arab Emirates (the), but it is not yet operational.

Benefits:

- The increased wall-size allows large amounts of heat to be transferred from inside the greenhouse to the ambient air without losing water and requires less artificial ventilation.
- The humidity and temperature of the greenhouse air will be lower than that of the desiccant greenhouse (although the temperature will still stay well above average ambient temperature).

Limitations:

- Increasing the greenhouse surface will require an improved greenhouse design, which must have low construction costs.

A desiccant greenhouse can be made more efficient by further heating the storage using a source of residual heat, such as a power station or a solar pond (Figure 5.9). If night-time temperatures are high, then the surface between the greenhouse and the ambient air must be increased to release additional loads of heat.

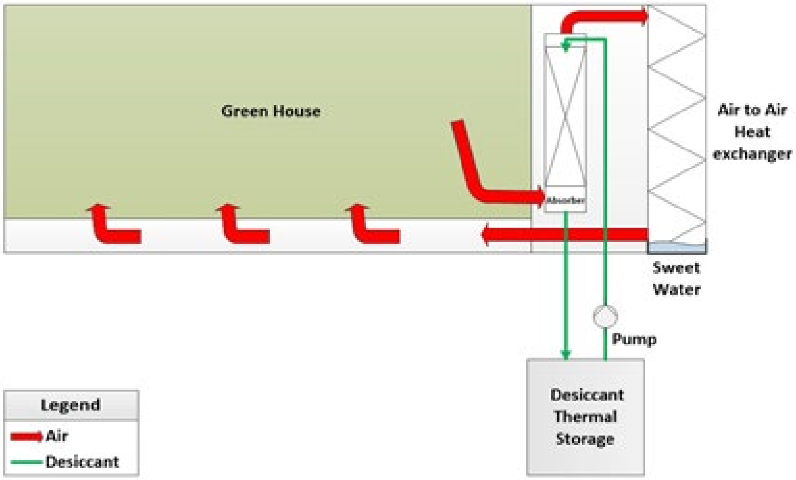

Figure 5.9 A desiccant greenhouse made more efficient by heating the storage using a source of residual heat

Source: *Watergy GmbH, 2020.*

5.2 INTEGRATED LAND MANAGEMENT USING NGGH FOR CLIMATE CHANGE ADAPTATION

5.2.1 USE OF PRETREATED WASTEWATER IN CLOSED PRODUCTION SYSTEMS

In general, agricultural production in arid areas is limited primarily by the availability of water. In NGGH systems, fresh water can be partially recycled or replaced with sea or brackish water. Closed greenhouse technology aims to recover water from the air and recycle the water evaporated by the plants.

If wastewater is used for greenhouse irrigation (in a manner that controls safety issues), the water that is recycled in greenhouses can be a source of potable water, using the vegetation's root membranes as the most effective and self-renewing water filter available.

Once the plants absorb the water, the nutrients contained in the wastewater can be used for growth and the water that is evaporated is completely purified. The vapour can then be transformed again to a liquid state by cooling the air below the dew point, using a cooling system.

Communal wastewater has a high content of plant nutrients, but the inappropriate use of such water can cause diseases. Therefore, wastewater must be fed into irrigation systems without coming into contact with above-ground parts of the crops. This can be managed using hydroponic systems, where a sub-ground free flow of water in gravel or other porous substrates distributes the water. Another possibility is a modified drip irrigation system, where water is distributed above ground but is injected directly into the ground or placed under a foil layer.

The use of pretreated wastewater in agricultural irrigation may replace more complicated nitrogen and phosphorus elimination strategies. Biological pre-treatment can already reduce the content of plant nutrients, so a wastewater treatment system integrated into horticultural irrigation can be interpreted as a complete alternative method, using minor, simple pre-treatment strategies. Highly polluted water – for example, water with a higher content of heavy metals – can be used only for irrigating non-edible biomass. While the production of energy crops will not be sufficiently economical, the production of regenerative material can be an interesting alternative to food crop production. A closed greenhouse with biomass crops may contribute to producing a surplus of condensed water, which can then be used in greenhouses producing food.

Figure 5.10 illustrates a closed water cycle between a closed greenhouse and an urban area, with a condensed water supply for the building and grey water for irrigation. Treated urine is used as a liquid fertiliser, and composted faeces are used as a soil enhancer. Rainwater and seawater that is desalinated in the system can replace the small amount of water lost through evaporation or can even produce a water surplus for open-field horticulture.

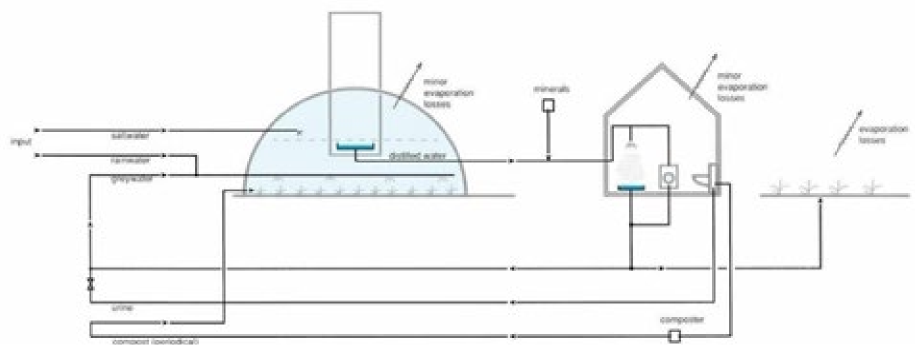

Figure 5.10 A closed water cycle between a closed greenhouse and an urban area

Source: *Technische Universität Berlin, 2003.*

Grey water is the wastewater of an urban area without the faeces or urine. It includes water from washing machines, showers, wash bowls, etc. The method used in this system radically reduces the hygiene and odour problems related to wastewater. However, the nutrient content of the grey wastewater is very low. Urine contains 70 percent more plant nutrients than urban grey waste water. Separate collection of urine and faeces reduces the volume of faeces in collected urine to about 10 percent. Faeces can be collected in compost or vacuum toilet systems, while urine can still be collected with simple liquid and gravity-based collection systems. Such a system can reduce the need for urban fresh water by about 25 percent. Collected urine can be used after simple pre-treatment in modern automated nutrient supply irrigation systems without hygiene problems.

Composted faeces can be used for biogas production. Another option is to generate energy combining faeces with agricultural waste and any other biological waste, by means of pyrolysis. In this process, part of the hydrocarbons are converted into pyrolysis gas and pyrolysis oil, while a certain part of the carbon remains as charcoal and can also be used as a long-term, stable soil enhancer in greenhouse container culture. Charcoal contributes to a higher soil water content and, thus, may also contribute to higher thermal capacity of greenhouse soil, which improves the climatic functioning of the system.

These substrates can also be recycled, as roots and organic compounds and pests can also be converted into charcoal after further pyrolysis treatment.

5.2.2 CLOSED ECOSYSTEMS AND A CLOSED CARBON CYCLE WITH CO_2 AS A PLANT NUTRIENT

Similar to closed greenhouses, in which plants produce oxygen and absorb CO_2, which is constantly used as a plant nutrient, a natural next step in imitating biosphere processes is to implement production components that include consumer populations that absorb oxygen and release CO_2. These can be established by integrating productive components of solid-state fermentation, where biomass is transformed into useful products such as protein-enriched vegetables, de-lignified fibre products with smoother quality, de-lignified wooden biomass for pulp and paper production or production of a large number of enzymes for use in diverse chemical processes. Composting is a related application that can be used to enhance soil but can also be used to remove organic pollutants and to produce heat during winter periods.

Solid state fermentation is the management of fungal growth on the wet surface of treated biomass. It includes constant removal of heat and CO_2 and a supply of oxygen by ventilation, but it also provides a constant level of humidity, through substrates.

This process can be perfectly combined with the climate control of closed greenhouses by using induced internal air circulation and by creating a hot, tropical-like basic climate. Tempeh is a food product produced by solid-state fermentation of soya or peanuts. The quality of the synthesized proteins is very high, and production cycles are much faster than those of meat or fish. It has a high potential as a major protein source in future human nutrition. This is of greater importance as there is a limited supply of fish, and mass cultivation of animals is linked to growing environmental problems, including greenhouse gas emissions.

One method of solid-state fermentation is the use of tray bioreactors. These can be placed in closed greenhouses (Figure 5.11). The fermentation process profits from the plants' oxygen supply, the hot/humid climate and the removal of CO_2 and heat in the internal air circuit.

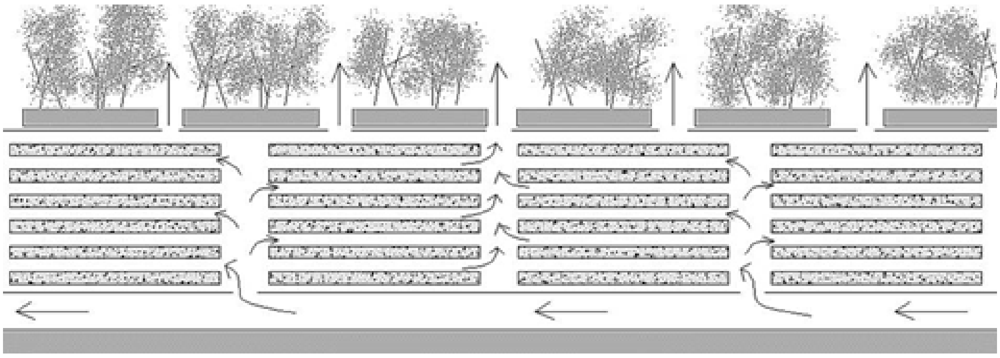

Figure 5.11 Tray bioreactors

Source: *Buchholz, 2002.*

5.2.3 CLOSED GREENHOUSES AND RELATED SOIL SYSTEMS AS CO_2 SINKS

In a closed greenhouse, carbon dioxide can be artificially increased to an optimum level for plant development. When other productive factors, such as water, nutrients, temperature and light are optimized, CO_2 triggers growth, and optimum rates can be around 1 200 ppm (~triple atmospheric level) – much higher than in open-field agriculture. The higher growth also contributes to a higher production rate per unit of water.

CO_2 can be supplied directly from combustion processes, where emissions have to be pre-cleaned to allow a supply of pure CO_2. These technologies are commonly used in greenhouse horticulture, but only a closed greenhouse can contain the gas, use it efficiently and provide the required conditions to reach optimum levels of concentration, in the range of 800 to 1 200 ppm CO_2.

A further possibility is to use CO_2 previously collected in external combustion processes and buffered in storage media.

A negative CO_2 balance can be reached in greenhouse production systems if edible biomass is provided to consumers, and urban waste, together with agricultural waste and solid organic matter from wastewater, is redirected as plant fertilizer or soil enhancer.

Non-edible biomass can be used as a resource for building materials, paper, textiles, etc., and carbon is stored for a longer period, but finally appears as waste. Waste and non-edible biomass can be used for composting or combustion processes, preferably through pyrolysis where gas emissions are cleaned and redirected into the greenhouse, and the remaining charcoal is used as stable water and nutrient storage in the greenhouse soil or open fields. (Note that charcoal can be a long-term carbon sink for periods of over a century.) Charcoal-based soil systems also have good heat storage ability, which again is favourable for the climate control system of NGGH.

A second way to achieve a negative CO_2 balance comes with the factor of growth. As closed greenhouses allow intensive production in places where no reasonable biomass accumulation was possible before, additional carbon dioxide is fixed, even if the balance only indicates a short-term deposit.

5.2.4 CONCEPTUAL CONSIDERATIONS FOR ENHANCING RESILIENCE TO CLIMATE CHANGE THROUGH THE ADOPTION OF CLOSED GREENHOUSE TECHNOLOGY

Strategies to combat climate change cannot be simplified to only reducing greenhouse gasses in the atmosphere. They must consider a change in the earth's surface structure in order to decrease the area of hotspots.

In the biosphere, the surface is cooled by evaporation from plants. In a forest, up to 85 percent of the energy input of the sun is transferred, by water evaporation and transpiration, back to the atmosphere. This part of the energy is stored as latent heat and is gradually released. Part of the heat is radiated back into space at the moment when a cloud emerges, and part of it radiates back to the ground but is distributed during the night, finally leading to an equalization of temperatures.

Two processes are constantly deteriorating the biosphere. In humid climates, agriculture, deforestation and industrialization are creating surface structures with reduced metabolic rates. This means reduced photosynthesis (reduced CO_2 consumption), reduced carbon content in the soil, reduced water storage capacity in the soil and, as a result, reduced evaporative cooling. In arid climates, desertification creates a process that degrades the quality of the surface without human intervention with the same results.

Once a hotspot is created, the thermal lift results in reduced rainfall, the small water droplets within clouds are re-evaporated, or clouds are moved around the area because of thermal lift.

A global strategy against climate change could be triggered by starting at the coastlines, where desalination and the management of other unconventional water resources, such as wastewater recycling, rainwater harvesting and water capture from air humidity, can build the principal base of human economic activities, in addition to reducing greenhouse gas emissions within hot/arid regions. This process will also realize a huge growth potential for climatic-enhanced surface structures in arid or desert lands.

The function of surface cooling works differently in relation to new greenhouse technologies than it does in the open biosphere. Evaporative cooling is again the major driving force, but related condensation is forced to take place within the closed greenhouse. Water is saved, and the sensible heat that is released is transferred to water or desiccant fluids and stored.

Furthermore, the water content of the soil and the related heat capacity can be enhanced through the accumulation of carbon compost or charcoal as a long-term, stable soil enhancer. Water and heat are kept on the site and can stabilize the climate conditions of the surrounding area. The energy balance of existing prototype greenhouses shows that a major part of the radiated energy still escapes through the greenhouse cover, but in terms of cooling peak radiation levels during the daytime, already over 50 percent of the solar radiation is captured and stored in the soil and the thermal storage during the daytime and then released at night. This kind of energy balance provides a much better cooling effect than evaporative cooling from drought-adapted agriculture, like in the cultivation of olive trees or date palms.

Moreover, the method of additional evaporation of seawater in closed systems can be further developed and will enable greater retention of thermal energy as well as corresponding higher yields of condensed water.

As shown in Figure 5.12, in arid climates, a major portion of the solar radiation (see the white column – a 5-day sequence in April, in southern Spain) is directly transferred into sensible heat and warms the surrounding air above the soil, while the heat flux in a closed greenhouse shows that parts of the energy here is first transferred into evaporation of water, condensed on a heat exchanger and then buffered in a storage to be released during the night (blue column). The higher water content of the soil does not result in water loss and allows a higher heat transmission into the soil, which contributes to another major heat retention (grey column). Evaporation, which normally leads to water loss in conventional greenhouses, is limited to minor losses out of the enclosure (yellow column). In this way, a major portion of the heat flux is stored into the night-time (yellow/blue column as source of heat, and green column as heat release). Surface cooling during the daytime and heating during the night-time both mitigate the effects of a typical desert climate.

The essential impact is a reduction of surface temperature during daytime, which in the Gulf region is reduced from between 60 and 80 °C to 40 °C.

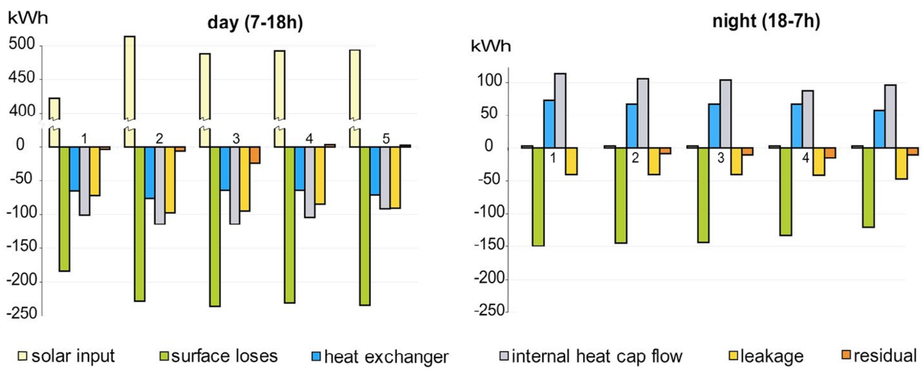

Figure 5.12 Heat flux in closed greenhouse

Source: *Buchholz, 2006.*

5.3 ECONOMIC AND ENVIRONMENTAL COST-BENEFIT AND TRADE-OFF ANALYSIS OF THE NGGH SYSTEM

In this section, conventional greenhouse production systems are compared with the new desiccant greenhouse systems. These are closed greenhouses, which allow constant air dehumidification, while constant evaporation from the greenhouse crops provide coolness.

When a state of the art greenhouse system is working in open mode, dry air from the outside is ventilated into the greenhouse and the more humid air from within the greenhouse is released outside. Water that evaporates from the plants is released into the environment. This provides cooling, but the water is lost to the environment. In a closed greenhouse, water is captured and recycled during the night, through a combination of desiccant regeneration (water is evaporated out of the desiccant solution using stored heat) and water condensation on the inner surface of the greenhouse covering material. In this system, water is kept inside the greenhouse system, but at the expense of a higher diurnal average temperature inside the greenhouse.

A benefit of a closed greenhouse is the possibility of CO_2 enrichment. This is also possible in open greenhouses, but due to the air exchange, a large portion of this gas (~90 percent) is lost to the environment. CO_2 enrichment can be provided through a gas combustion process (such as a combined heat and power unit or a gas motor), from bottled CO_2 or by CO_2 provided from biological activities (bacteria, mushrooms, animals or humans).

Closed greenhouses are not new, but dehumidification normally is provided by a cooling process that requires a large amount of mechanical energy (fossil sources of energy), while a desiccant system is based on solar thermal energy or residual heat.

Compared to other greenhouses, desiccant greenhouses must be provided with additional air conditioning infrastructure and, thus, have higher investment costs. The components required for this include absorber and desorber elements to draw humidity from the air (during the daytime) and desiccant regeneration during the night-time. The second crucial part is thermal storage and desiccant storage. Here, the costs consist of the containment and the desiccant fluid. The third major additional investment is in equipment for desiccant and air transport. Furthermore, the construction of desiccant greenhouses requires additional investment for improved removal of condensed water and improved heat transmission through the greenhouse cover.

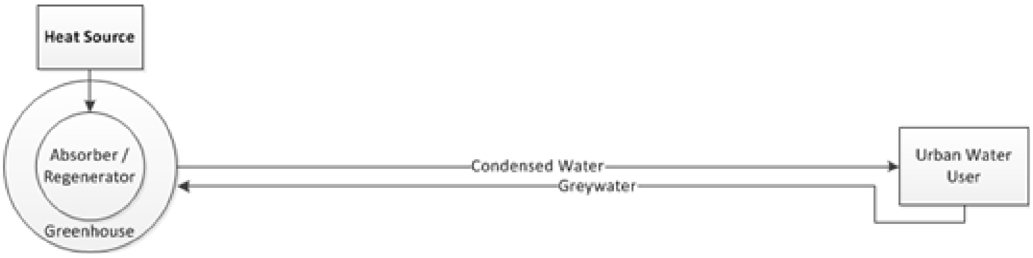

Figure 5.13 Desiccant system

Source: *Technische Unversität Berlin, 2015).*

The desiccant system operates within the greenhouse, where absorption collects water from the vegetation, while desorption allows the water to be recovered (Figure 5.13). Outside components are heat networks to external sources of residual heat (such as a concentrated solar power [CSP] plant) and water networks, exchanging impure water and clean, condensed water.

A big difference between the desiccant cooled greenhouses in comparison to state of the art greenhouses or air-conditioned-cooled closed greenhouses is that the diurnal average inside temperature is permanently 5 to 10 degrees warmer than the diurnal average outside temperature, not only in the daytime, but day and night-time.

Greenhouses can only reach temperatures below the average outside temperature when cooling sources are used that can extract large amounts of energy, reducing the inside temperature some 10 to 20 °C below the diurnal daily average temperature. Such cooling sources can be natural (deep ocean seawater, seawater evaporative cooling), or artificial (chillers).

5.3.1 VALUE PROPOSITION

The overall challenge is to increase production in protected agriculture under use of high CO_2 levels by integrating water recycling on land without available fresh water sources and under harsh climatic conditions.

Despite the higher investment costs, the desiccant greenhouse concept provides additional income in four different areas:

1. INCREASED PRODUCTIVITY

A closed greenhouse can use almost any level of CO_2 enrichment, as no air is ventilated out of the greenhouse. This allows crop production at increased CO_2 levels, which leads to considerably higher yields due to improved photosynthesis.

2. WATER EFFICIENCY

As the water evaporated by the vegetation in closed greenhouses is not ventilated to the environment but, rather, is kept within a closed water cycle, water efficiency is increased by a factor of 20. The only water lost is that which is lost through minor leakages in the greenhouse cover. If grey water is used for irrigation, the water that is captured through the condensation process is recycled. In this way, not only is water saved but it is also valorised through the uptake of impure water (water cleaning services) and the sale of condensed water as a source of urban fresh water.

3. LAND SUITABLE FOR GREENHOUSE CROP PRODUCTION

The water saving function affects the price of the agricultural land, as the horticultural production can be carried out on land with much lower water availability and with larger differences between hot and cold temperatures. Today, intensive horticultural production is limited to places with mild climates and available groundwater. This configuration, together with the prospect of high profits in protected agriculture, greatly increase the value of the land. For Spain, the value of the land suited for intensive horticulture, can be around ten times higher than that of land used for rain-fed agriculture. As a reference, in 2018, 1 m^2 of irrigated land in Almeria cost around 10€.

4. COOLING SERVICES

Desiccant greenhouses in areas with higher night-time temperatures (including the Gulf region) require higher temperatures for desiccant regeneration. A night-time temperature of 30 °C, for example, requires a desiccant temperature of around 50 °C, but the desiccant greenhouse can only operate during the day at a maximum of around 45 °C, thus providing storage temperatures of around 40 °C. The highest added value is achieved with a combination of the desiccant greenhouse with external facilities providing residual heat and requiring cooling services. This can be a thermal power station or space cooling facilities from buildings or industry. These facilities require large amounts of electric power for cooling, especially for ventilation, if the residual heat is released in a dry process. Evaporative cooling requires less energy as less air has to be ventilated. However, large amounts of water are required.

In combination with a closed greenhouse system, residual heat can be conducted from a cooling cycle to the greenhouse thermal storage. The heat can be used for improved desiccant regeneration, where water evaporates out of a saline solution, providing a solution concentrate as the upgraded product. In this way, a closed greenhouse system also serves as a kind of "horizontal cooling tower" for power stations or air conditioning equipment. For example, the greenhouse may serve a CSP power station in the desert, where water for cooling is not available.

State of the art, in this case, is dry cooling, with the disadvantage that a larger portion of produced power is required for running fans. This greenhouse system provides a means of evaporative cooling that consumes less power in the cooling chain.

Figure 5.14 illustrates a desiccant greenhouse layout with integrated power production. This can be a concentrating solar system, such as a Fresnel mirror, or a mirror only reflecting infrared light. The heat produced is directed to a power unit and cooled back by the desiccant cycle (red lines). During the daytime, the cold desiccant is first used for greenhouse dehumidification. Afterwards, the fluid is further heated by the power cycle and then stored in a day/night thermal storage unit. During the night-time, the heat is used for desiccant regeneration, and the water is condensed on the inner surface of the greenhouse cover.

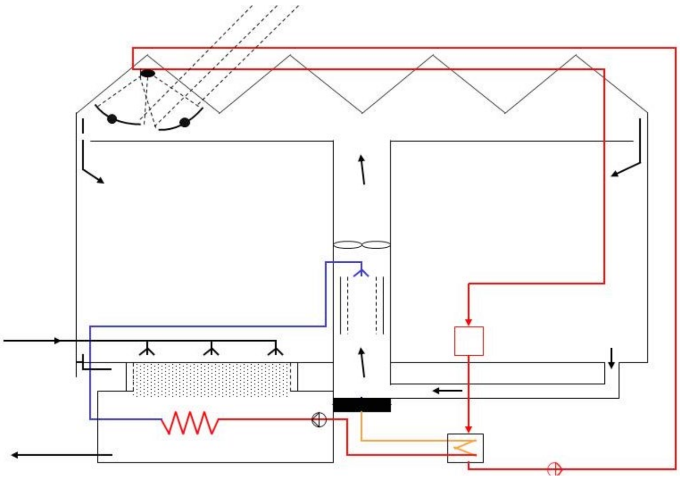

Figure 5.14 Desiccant greenhouse layout

Source: *Watergy GmbH, 2015.*

5.3.2 COST-REVENUE ANALYSIS FOR A DESICCANT GREENHOUSE SYSTEM COMPARED TO A STATE OF THE ART PRODUCTION GREENHOUSE IN AN ARID CLIMATE

The following table shows a comparison of a state of the art horticultural greenhouse on arable land with sufficient water availability to a desiccant greenhouse on a site of low-quality land. The investment costs calculation shows higher costs for technical equipment (mainly for climate control) for the state of the art horticultural greenhouse as well as costs related to the high-quality land allowing profitable greenhouse-based production.

This calculation assumes there is water available and a mild climate, with no need for additional heating.

The main difference between a conventional open greenhouse and a closed greenhouse is the level of investment costs. In particular, the climate control equipment for the closed greenhouse is much more expensive. These costs are partially balanced by the higher cost of land with sufficient conventional water availability required for conventional production. In total, the cost of a closed greenhouse is slightly less than double the cost of a conventional one (calculated for a 20-ha farm).

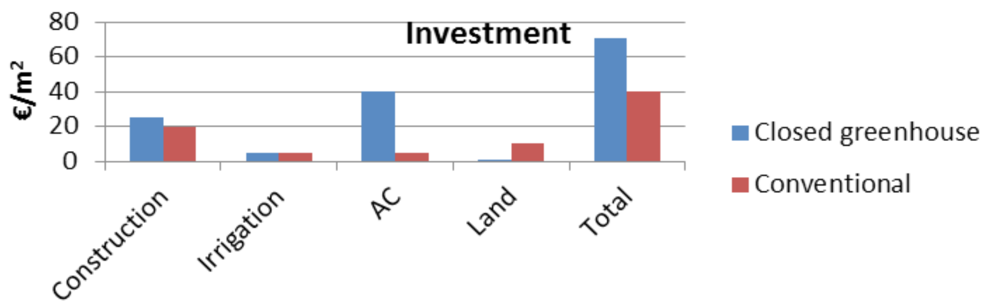

Figure 5.15 Investment costs

Source: *Technische Unversität Berlin, 2015.*

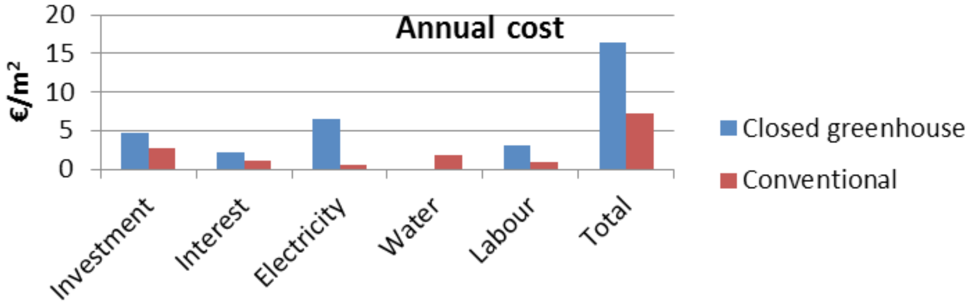

Figure 5.16 Annual running costs of the two systems

Source: *Technische Unversität Berlin, 2015.*

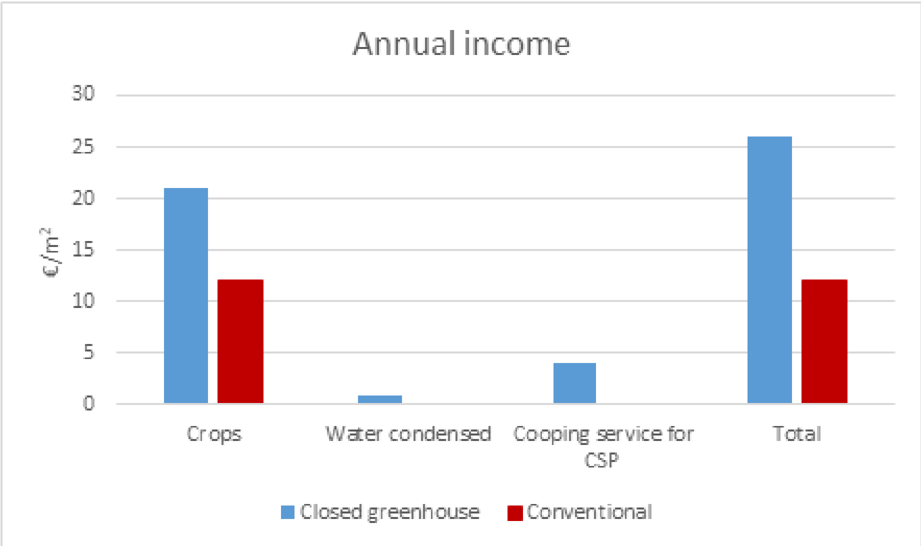

Figure 5.17 Annual potential profits of the two systems

Source: *Technische Unversität Berlin, 2015.*

The higher annual income compensates for higher investment costs. The higher income is a result of higher production (resulting from the use of CO_2 in the greenhouse atmosphere) and income from water produced in the greenhouse and from cooling services for external sources of residual heat (Figure 5.18).

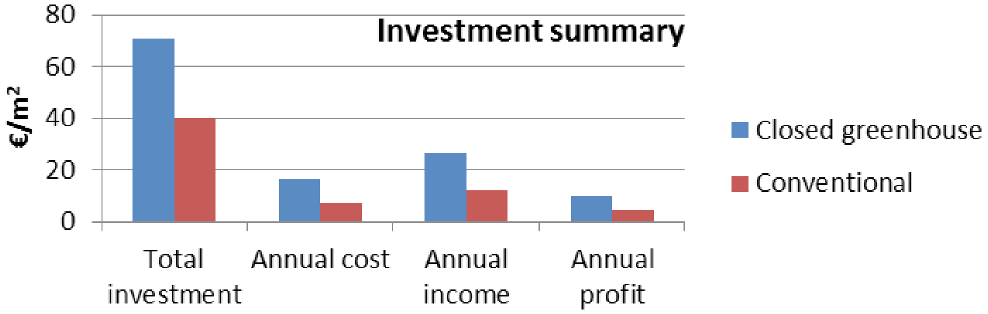

Figure 5.18 Annual running costs of the two systems

Source: *Technische Unversität Berlin, 2015.*

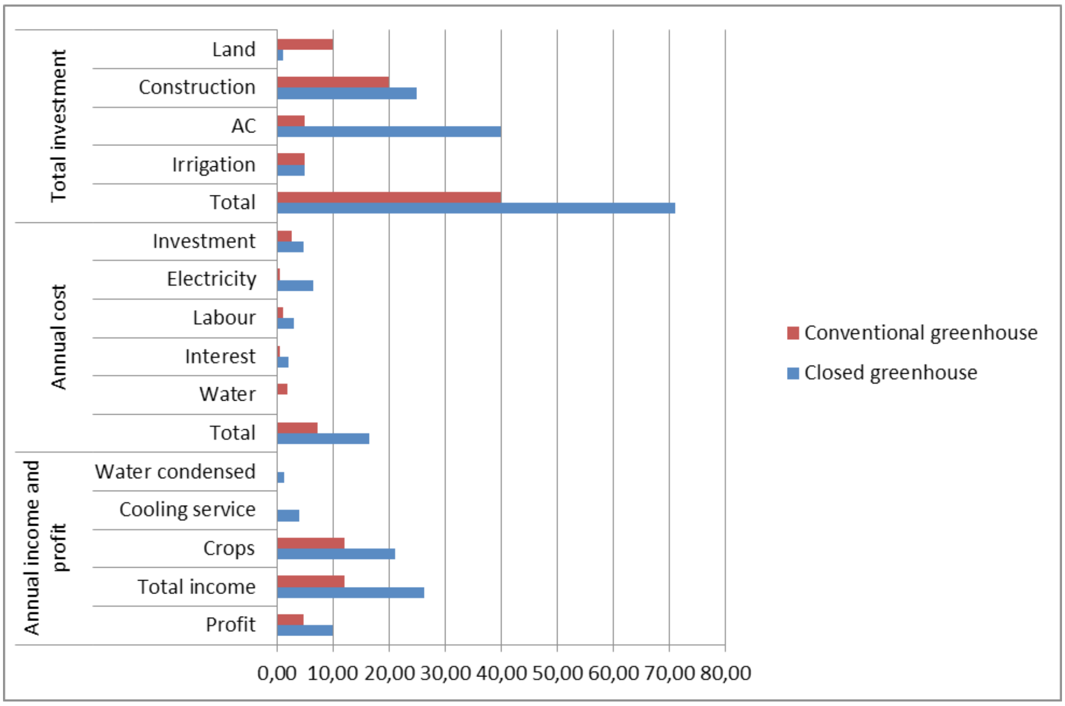

Figure 5.19 Full comparison of conventional and closed greenhouse systems

Source: *Technische Unversität Berlin, 2015.*

The full comparison (Figure 5.19) shows that the two systems have similar payback periods (7 vs 8 years) but have very different specific costs. The closed greenhouse has higher annual costs, but also provides much higher income, resulting in a higher annual profit.

5.3.3 SIZING OF THE CLIMATE CONTROL EQUIPMENT AND SEASONAL OPERATION OF THE GREENHOUSE

As stated above, the climate control equipment of a desiccant greenhouse system is the highest cost factor in comparison with state of the art open greenhouses. A general approach for optimizing the economic balance is to minimize this cost. There are two possible approaches to achieve this:

- Approach 1: Optimising the system for nine months: During the hottest three-month period in summer, the greenhouse is empty or is used for crops with high heat tolerance such as some non-food fibre crops. In this way, investment costs for climate control can be reduced by 40 percent. The total annual production of crops during the remaining nine months can still be higher than in a conventional greenhouse due to CO_2 enrichment. Fibre crops can compensate ~30 percent of the interrupted production of cash crops (tomatoes, cucumber, etc.).
- Approach 2: Optimising the system for full operation during 12 months, with increased capacities of the absorber, storage and hydraulic system: The additional capacities compared to the first approach scenario are only needed for three months, but they can also be used during the nine-month period for additional evaporation of impure ore saline water and related additional fresh water production. Profit of crops in the hot season will be lower due to higher costs. Equipment for additional climate control during this period is not economically beneficial. This scenario is only viable if an adequate market price for the water produced is achieved. This is especially the case if water is provided to remote places via trucks (price >USD 4/m^3).

5.3.4. ENVIRONMENTAL IMPACT

Environmental issues of protected horticultural cultivation, in general, are related to the material used for the construction of the greenhouses (mainly steel construction, with glass or plastic cover material, and various materials for crop containers, irrigation systems, etc.) and related sources of waste (especially plastic waste) after the period of use.

Another significant environmental impact is related to the use of mineral fertilizers and pesticides inside the greenhouse, which could potentially pollute the soils and groundwater in the area as well as the air and surface water. Additionally, biological and agricultural waste is produced and often is not removed properly, leading to an uncontrolled heating process within provisional compost heaps.

- As regards the environmental impact of protected cultivation, it should be born in mind that protected cultivation is a relatively new practice with very high potential for growth. As such, major progress will likely be made in the following aspects, increasing the sustainability of the technology:

- Construction materials can also be made of renewable materials and salt-born plastics that can potentially be reproduced by the productive system itself, thus minimising the environmental impact.
- Fertilisers can be produced from organic waste using solar energy (utilising the Haber–Bosch method for nitrogen fixation) and from seawater (harvesting especially potassium through solar water evaporation and concentration management).
- Biological crop protection (using natural predators against insects) is already practised in many greenhouses today.
- The impact on the soil and groundwater can be reduced through better control of the irrigation water and nutrient re-use within a closed water cycle.

5.4 OVERALL APPRAISAL AND FUTURE PROSPECTS OF NGGH IN THE GULF COOPERATION COUNCIL COUNTRIES

The overuse of fossil groundwater is not a real environmental issue, but more a resource problem. However, reducing the need for non-renewable water and increasing the use of seawater and brackish water can have a positive impact on the regional climate, as described in the next section, as well as improving biodiversity.

The daytime surface temperature in a desert is 60 to 80 °C. This is why there is no rainfall, as such temperatures are causing buoyancy draft of hot air.

A closed greenhouse with thermal storage and improved soil conditions in both container based and soil-based systems will lower surface temperatures in the area of greenhouse production. Used on a large scale, this can also influence the climate in the surrounding area, lowering daytime temperatures and increasing night-time temperatures. The effect would mitigate the temperature amplitudes in the desert climate.

The main improvement in climate impact is a result of the reduced heat emissions to the environment during the hot period of the day. If residual heat is released into the environment, it is usually related to a negative impact. This is mainly the case for heat emissions from industry or power production releasing waste heat to surface water bodies like rivers or lakes. The greenhouse system can use this heat for desiccant regeneration and heat release during the night-time period. An increased desiccant concentration then helps to improve greenhouse climate control during the daytime.

Dry emission to air adds to the urban heat island effect, while evaporative cooling involves high water consumption and may cause hygiene impacts such as the development of legionella bacteria.

A closed water cycle within a greenhouse has several positive impacts, including the following:

- Solar input is converted to evaporation by the vegetation, thus reducing the surface temperature of the land.

- Residual heat sources in the range of 40 to 60° C can be captured by the greenhouse system in its thermal storage unit that is used for internal greenhouse cooling functions.
- Heat emissions are partially shifted from daytime to night-time at lower ranges of temperature.

For the regional climate of the conurbations in the Arabian Gulf, closed environment greenhouses that allow for surface cooling without emitting humid air will greatly improve the climate. This is beneficial, as further water evaporation to the environment would contribute to lower temperatures at the price of increased humidity, while the total air enthalpy will remain the same. For the quality of life in the cities, it would be better to only reduce the temperature without increasing humidity, as HVAC cooling and dehumidifying systems do.

In the desiccant greenhouse system, the desiccant fluid remains within the greenhouse system, while heat is moved from external heat sources to the greenhouse system. As such, the greenhouse must be located close to the heat source. This may be problematic if the land around the heat source is expensive. Future applications must be developed to achieve optimal configurations. The urban setting can be optimized, if residual land (that is, land along traffic corridors or on top of buildings, parking sites, etc.) is used.

Desiccant greenhouse technology might provide a completely new application of water management, and food production as a potential solution for climate adaptation, especially in harsh climate conditions.

The specific new characteristic of the technology is its water cycling system: water is maintained within closed cycles. As such, the water saving perspectives of the technology are attractive, and there is a high potential for growth.

Once it is possible to regenerate more desiccant than is needed for internal greenhouse control, the desiccant solution can be used to pick up water from surrounding open evaporative cooling devices. In this case, the network would also have to be designed for this kind of application.

It is possible to recover from the higher investment costs required for such a system and to reach a level where closed greenhouses can be established on a large scale, especially in the periphery of urban areas and in coastal zones, because this technology comes with additional advantages, including the following:

- greater plant growth at increased CO_2 levels;
- the possibility of recycling wastewater;
- seawater desalination;
- water absorption from ambient air;
- the possibility to implement further productive processes, such as the cultivation of renewable materials;
- solid-state fermentation; and
- regeneration of desiccant solutions.

Additionally, the probability of higher rainfall in the surrounding area is increased by reducing the surface temperature at a sufficient scale.

5.5 NETHOUSES

Figure 5.20 compares a simple nethouse with a fog cooling system to a conventional greenhouse with fan and pad cooling in the GCC countries. [2]

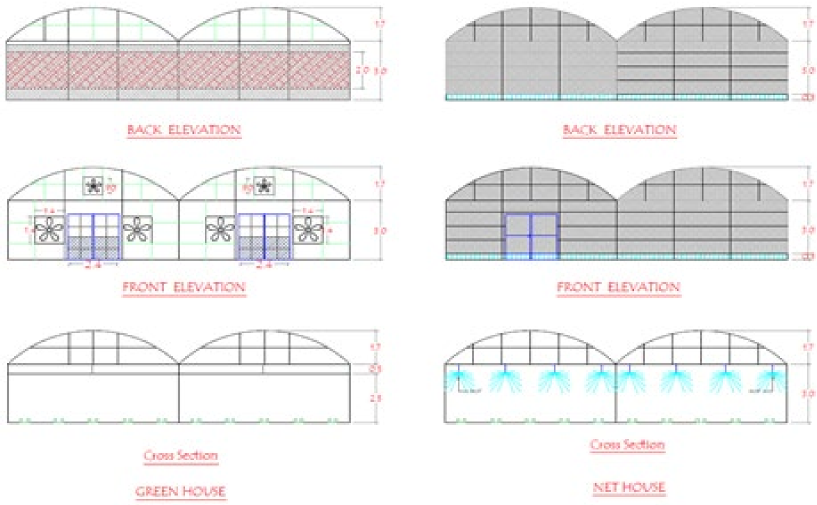

Figure 5.20 Greenhouse and nethouse technical specifications

Source: *Hirich and Choukr-Allah, 2017.*

5.5.1 WATER USE

The average water use for cooling and irrigation recorded under greenhouse and nethouse production is presented in Figure 5.21. Data reflect the increase in average water use during the production cycles, where maximum cooling and irrigation water use was recorded during the third production cycle. During this production cycle, the cooling process under a greenhouse consumed 224 % the amount of water used for irrigation, while under nethouse production, the cooling process (with a fog system) consumed only 160 % of the amount of irrigation water applied.

2 Data refer to a study carried out in United Arab Emirates (the) on a -3cycle cucumber cultivation on substrates conducted by Choukr-Allah and Hirich - of ICBA.

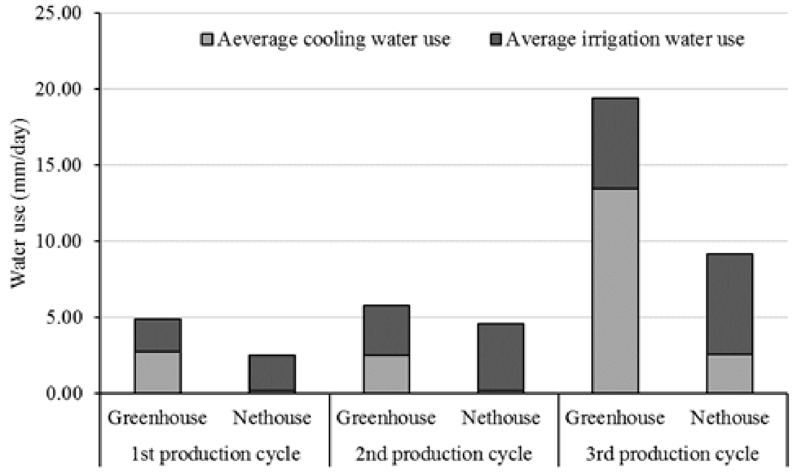

Figure 5.21 Average water use for cooling and irrigation under greenhouse and nethouse

Source: *Hirich and Choukr-Allah, 2017.*

The total water use under greenhouse and nethouse production for the three production cycles is equal to 2 321 and 1 238 mm respectively, which indicates that the greenhouse production consumed twice the amount of water compared to the nethouse production. Figure 5.22 shows also that the cooling process consumed only 21 percent of irrigation amount under nethouse production while under greenhouse production the cooling process consumed 160 percent water compared to irrigation supply. The data indicate also that the irrigation supply was higher under nethouse production, with an increase of 15 percent compared to greenhouse production, which can be explained by higher evapotranspiration due to the higher temperature.

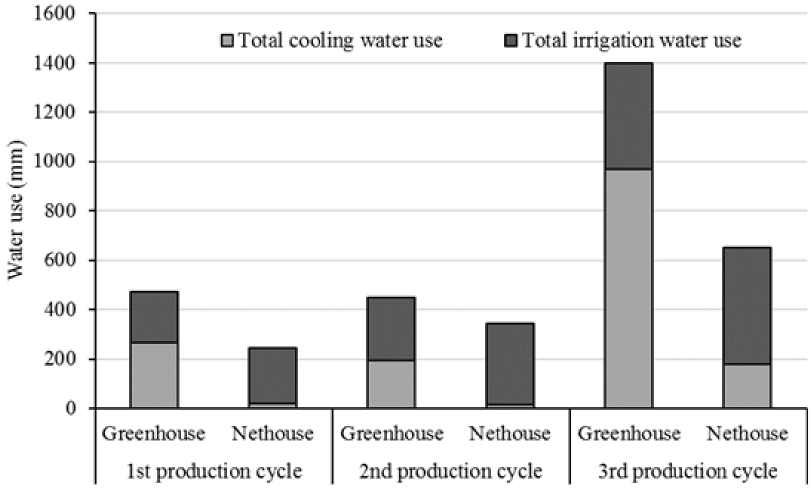

Figure 5.22 Total water use for cooling and irrigation under greenhouse and nethouse

Source: *Hirich and Choukr-Allah, 2017.*

5.5.2 ENERGY USE

Table 5.1 presents data related to energy use. Energy consumption under nethouse production is 98 percent less than in that of greenhouse production. Total energy for irrigation represents 1.26 percent and 90.62 percent of the total energy consumption for greenhouse and nethouse respectively. The findings indicate that most of the energy consumed in greenhouse production goes to cooling, while most of the energy in nethouse production goes to irrigation.

Table 5.1 Average and total energy use under greenhouse and nethouse conditions

Energy use	1st production cycle	2nd production cycle	3rd production cycle	All cycles
	*GH	**NH	GH	NH
Average cooling energy use (Wh/m2.day)	151.3	0.1	133.8	0.1
Average irrigation energy use (Wh/m2.day)	1.6	1.7	2.5	3.3
Total cooling energy use (Wh/m2)	14675.0	6.7	10433.9	5.4
Total irrigation energy use (Wh/m2)	152.4	169.3	191.7	246.3

*GH: Greenhouse, **NH: Nethouse

Source: *Hirich and Choukr-Allah, 2017.*

5.5.3 WATER AND ENERGY USE EFFICIENCY

Figure 5.23 shows the water and energy use efficiency during all cucumber production cycles. The data indicate that water use efficiency (WUE) and energy use efficiency (EUE) were much higher in nethouse production than in greenhouse production. Overall, 1 m^3 of water produced 22 and 24 kg of cucumber grown in greenhouses in local and imported substrate, respectively. While 1 m^3 produced 42 kg of cucumber in nethouse production in local and imported substrates, which is the double the water use efficiency of the greenhouse production. The findings also show that 1 kWh of energy produced 1 and 61 kg of cucumber in greenhouse and nethouse production, respectively.

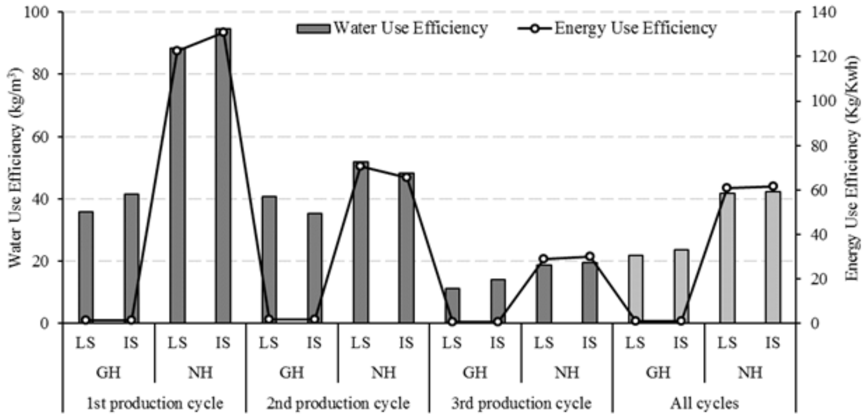

Figure 5.23 Water and energy use efficiency under greenhouse and nethouse conditions

GH: greenhouse, NH: nethouse, LS: local substrate, IS: imported substrate.

Source: *Hirich and Choukr-Allah, 2017.*

5.5.4 INVESTMENT

Table 5.2 presents the detailed costs of conventional greenhouses and nethouses (low technology). The cost of greenhouse structures per square meter is 1.5 times that of nethouses, mainly due to the expensive components of greenhouses, such as the covering material (e.g. polycarbonate). Other components related to pumping and drainage recycling, however, are required for both structures.

Table 5.2 Investment costs for greenhouses and nethouses (in AED)

Greenhouse components	Actual cost for 280 m²	Effective area (m²)	Cost for 1 m²
Span (35 x 8 m) covered by two layers of 6 mm thick PC sheet, equipped with pad and fans cooling system	47 500	280	169.6
Drip irrigation system	4 875	280	17.4
Drainage water system	28 000	10 000	2.8
Dosing unit	47 075	10 000	4.7
Technical room	43 200	50 000	0.9
Ground cover - 5 cm thick white gravel	6 375	280	22.8
Total greenhouse investment cost	**177 025**	**-**	**218**

Nethouse components	Actual cost for 280 m^2	Effective area (m^2)	Cost for 1 m^2
Span (35 x 8 m)	14 000	280	50.0
50 mesh white insect-proof net	2 000	280	7.14
Mist system	10 920	280	39.0
Drip irrigation system	4 875	280	17.4
Drainage water system	28 000	10 000	2.8
Dosing unit	47 075	10 000	4.7
Technical room	43 200	50 000	0.9
Ground cover - 5 cm thick white gravel	6 375	280	22.8
Total nethouse investment cost	**156 445**	**-**	**145**

Source: *Hirich and Choukr-Allah, 2017.*

Depreciation is calculated by dividing the initial investment of the total structure by the useful life period. Since the calculation will concern only the first research year, no discounted value will be updated.

Table 5.3 shows the depreciation for all the components of both greenhouses and nethouses. The nethouse structure depreciation is 15.6 percent less than the greenhouse structure.

Table 5.3 Investment life period and depreciation.

Greenhouse components	Useful life (year)	Cost AED/ m^2	Depreciation AED/ m^2 year
Span (35 x 8 m) covered by two layers of 6 mm thick PC sheet, equipped with pad and fans cooling system	15	169.6	11.31
Drip irrigation system	5	17.4	3.48
Drainage water system	15	2.8	0.19
Dosing unit	15	4.7	0.31
Technical room	15	0.9	0.06
Ground cover - 5 cm thick white gravel	15	22.8	1.52
Total greenhouse depreciation	**-**	**218**	**16.87**

Nethouse components	Useful life (year)	Cost AED/ m²	Depreciation AED/ m² year
Span (35 x 8 m)	15	50	3.33
50 mesh white insect-proof net	5	7.1	1.43
Mist system	10	39	3.90
Drip irrigation system	5	17.4	3.48
Drainage water system	15	2.8	0.19
Dosing unit	15	4.7	0.31
Technical room	15	0.9	0.06
Ground cover - 5 cm thick white gravel	15	22.8	1.52
Total nethouse depreciation	**-**	**145**	**14.22**

Source: *Hirich and Choukr-Allah, 2017.*

5.5.5 ENERGY COSTS

Energy costs concern the energy used for cooling, irrigation pumping and fresh water production. For the case under review, fresh water is produced by reverse osmosis as most of the groundwater in United Arab Emirates (the) is saline, so many farmers have installed reverse osmosis machines for fresh water production. Farmers in United Arab Emirates (the) pay 0.03 AED/KWh, as the government subsidises a portion of the price of energy. However, the actual cost of energy in United Arab Emirates (the) is much higher (0.25 AED/kWh) (Afshari and Friedrich, 2015). Table 5.4 presents the water and energy use as well as energy-related costs under subsidised and not subsidised energy scenarios. Monitoring of energy consumption and water production by reverse osmosis showed that 2.5 kWh of energy are required to produce 1 m^3 of desalinated water. In both scenarios (subsidised and not subsidised), nethouse production saves 93 percent of the energy cost.

Table 5.4 Energy use and costs under greenhouse and nethouse production, under subsidised and not subsidised conditions

Energy consumption		Unit	Greenhouse	Nethouse
Irrigation energy		Wh/m^2	667.90	769.70
Cooling energy		Wh/m^2	51 958.90	79.60
Fresh water produced		l/m^2	2 321.00	1 238.00
Fresh water production energy		Wh/l	5 802.50	3 095.00
Subsidised energy	Irrigation and cooling energy cost	AED/m^2	1.58	0.03
	Fresh water production energy cost	AED/m^2	0.17	0.09
	Total energy cost	AED/m^2	1.75	0.12
Unsubsidised energy	Irrigation and cooling energy cost	AED/m^2	13.16	0.21
	Freshwater production energy cost	AED/m^2	1.45	0.77
	Total energy cost	AED/m^2	14.61	0.99

Source: *Hirich and Choukr-Allah, 2017.*

5.5.6 SUMMARY OF RUNNING COSTS AND INVESTMENT DEPRECIATION

Table 5.5 shows that energy cost without government subsidies represent 36 and 3 percent of the total running costs in greenhouse and nethouse production, respectively.

Table 5.5 Summary of running costs and investment depreciation (in AED)

Crops	Greenhouse		Nethouse	
	Local substrate	Imported substrate	Local substrate	Imported substrate
Labor	7.86	7.86	7.86	7.86
Fertilizers	4.75	4.75	5.59	5.59
Pesticides	0.47	0.47	0.47	0.47
Substrates and pots	7.12	11.68	7.12	11.68
Seeds	4.32	4.32	4.32	4.32
Others	1.02	1.02	1.02	1.02

Table 5.5 (continued)

Crops	Greenhouse		Nethouse	
	Local substrate	Imported substrate	Local substrate	Imported substrate
Energy (subsidised)	0.12	0.12	0.12	0.12
Energy (not subsidised)	14.61	14.61	0.99	0.99
Running costs (energy subsidised)	25.66	30.22	26.5	31.06
Running costs (energy not subsidised)	40.15	44.71	27.37	31.93
Investment depreciation	16.87	16.87	14.22	14.22
Total cost (subsidised energy)	42.53	47.09	40.72	45.28
Total cost (not subsidised energy)	57.02	61.58	41.59	46.15

Source: *Hirich and Choukr-Allah, 2017*

5.5.7 POTENTIAL USE OF NETHOUSE TECHNOLOGY IN THE GULF COOPERATION COUNCIL COUNTRIES

It has been demonstrated that protected agriculture performs better than open-field farming in terms of crop productivity, irrigation water productivity and quality. Harmanto *et al.* (2005) determined that crop evapotranspiration inside greenhouses is 75 to 80 percent of the crop evapotranspiration computed with the climatic parameters observed in the open environment. Under desert conditions, greenhouse cooling is necessary, especially during the summer (May to September). However, cooling consumes a considerable amount of water and energy, especially with a pad and fan system. In the GCC countries, cooled greenhouses consume seven times more cooling water than nethouses. However, cooled greenhouses require 15 percent less water for irrigation than nethouses.

According to López *et al.* (2012) fog systems consume more energy (7.2 to 8.9 kWh) than pad and fan systems (5.1 kWh) for continuous operations over one hour. During the summer, fog systems operate frequently only during the hot hours (20 seconds every 5 minutes). However, pad and fan cooling systems operate continuously the entire day, consuming a considerable amount of energy, which can exceed 120 KWh per day during the summer. Canakci and Akinci (2006) analysed energy use patterns in greenhouses for vegetable production. They found that the operational energy and energy source requirements in greenhouse vegetable production varied from 23 883.5 to 28 034.7 MJ/1 000 m^2 and from 45 763.3 to 49 978.8 MJ/1 000 m^2, respectively. The energy cost ratio of the total production cost of four major greenhouse vegetable crops (tomato, pepper, cucumber and eggplant) was found to be approximately 32, 19, 31 and 23 percent, respectively, which confirms that non-subsidised energy costs represent 36 percent of the total running cost for cucumber production. However, the energy cost ratio for cucumber produced under nethouse production does not exceed 3 percent.

The nethouse is an efficient system in terms of water and energy use that can be operated without significant yield reduction during the period April to June, when most vegetables can be grown.

Figure 5.24 shows the recommended nethouse design, which includes a fogging and shading system. The shading system can be manually opened from November to March, when radiation and temperature are low, to allow more light incidence. During the hot season, from April to October, shading can be closed to reduce the radiation and temperature inside the nethouse.

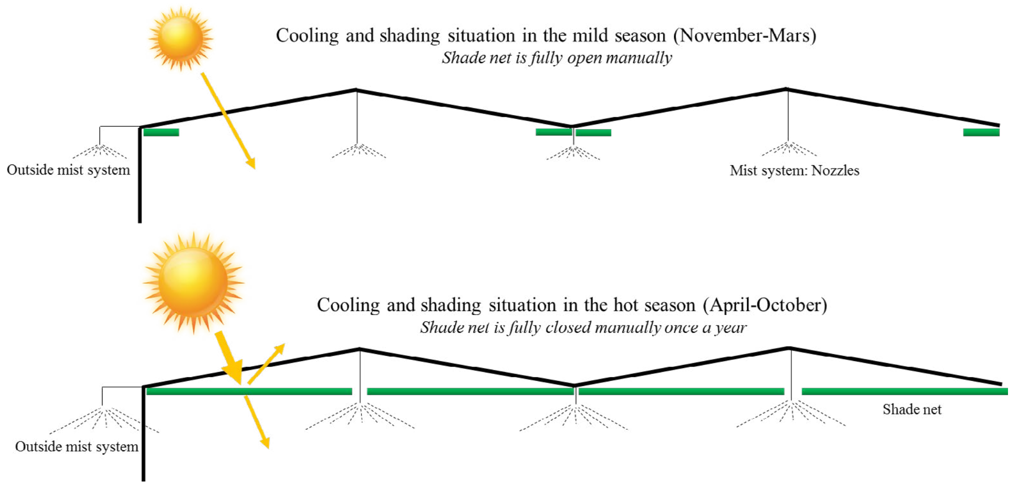

Figure 5.24 Design of the recommended nethouse

Source: *Hirich and Choukr-Allah, 2017*

Given the current situation of water resources and energy in the GCC countries, aggravated by climate change, conventional cooled greenhouses may no longer be a sustainable option for horticultural crop production. It has been shown that this system consumes a considerable amount of water and energy for cooling. However, the climate does allow for the production of a large number of vegetables between October and May (8 months) in nethouses, thus increasing crop water productivity, energy savings and income. Agricultural policies should consider the advantages of nethouses as an option to reduce the water and energy footprint under protected agriculture in the GCC region, versus the presently subsidised conventional greenhouses with pad and fan cooling.


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CHAPTER 6
RECOMMENDATIONS FOR DECISION-MAKERS

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CHAPTER 6
RECOMMENDATIONS FOR DECISION-MAKERS

6.1 INTRODUCTION

The main cause of groundwater depletion and deterioration in the GCC countries is the agricultural sector's unsustainable use of groundwater for irrigation. Furthermore, the GCC countries lack clear strategies for providing alternative water sources, once current sources have been depleted. Therefore, it is urgent that realistic agricultural policies and plans be developed that are compatible with the capacity of available water resources.

These plans and policies should focus on the use of renewable water resources and treated wastewater. They should guide the transition towards modern irrigation and agricultural methods, such as protected and soilless cultivation, in order to reduce water consumption and increase water yields. Given the economic and social consequences of depleting non-renewable groundwater, strategies must be developed and applied, which include balanced economic and social options for the use of water reserves and could include the transition to less water-dependent economies.

Such policies must take into account the economic and developmental aspects related to the provision of water services for drinking, agriculture and sanitation, including financing, investment, adaptive technology, the application of integrated water resource management principles and the development of non-conventional water resources. The plans and policies must also take into account the field of institutional development and the development of technical capacities as well as the development of social and individual awareness of the water problem in the region. This will require scientific research and enhancing the participation of civil society in decision-making with environmental implications.

To meet the challenges of integration into the global economy and to achieve sustainable levels of water consumption through conservation, agricultural policies must be re-examined with the dual objective of improving irrigation water use efficiency and improving the competitiveness of the agriculture sector. Agricultural reforms should also promote a market-oriented policy through the cultivation of high-water-productivity and low-water-content crops.

Among the aspects to be considered in agricultural reforms are the following: Agricultural research and extension should be developed. The use of non-conventional water resources (reclaimed wastewater, saline water and recycled agricultural water) should be increased.

Soil salinity should be reduced. Brackish and saline water should be used for cooling greenhouses, and the production of salt-tolerant crops with irrigation should be supported and expanded to develop a sustainable agriculture sector.

Various techniques have been introduced in the region, aiming to enhance the productivity of greenhouses, including integrated production and protection management (IPPM) and soilless cultivation. However, other important aspects of greenhouse production need to be further investigated in order to gain efficiency and sustainability related to cooling systems, conventional and renewable energy resources, and the range of crops to be grown in controlled environments.

6.2 TECHNOLOGY-BASED APPROACH, CAPACITY DEVELOPMENT AND NETWORKING

A technology-based approach requires two basic elements: skills and investments. These elements are linked as skills development requires huge investments in research and training, and investments require creative skills that can employ investments efficiently.

Given the current situation of water resources and energy in the GCC countries, aggravated by climate change, cooled greenhouses are no longer a sustainable option for horticultural crop production as they consume a considerable amount of water and energy. However, the mild climate between October and May allows for the production of a wide range of horticultural crops in nethouses without cooling, thus increasing crop water productivity, energy savings and income. On the other hand, some current agricultural policies such as subsidised energy lead to greater use of cooled greenhouses rather than encouraging sustainable protected agriculture.

One promising and innovative greenhouse technology is the desiccant cooled greenhouse, which provides a completely new application of water management and food production and allows solutions for climate adaptation, especially in arid and harsh climates. The new characteristic of this technology is its water cycling system, which, rather than economizing irrigation water, maintains the water in a closed cycle. This opens interesting new economic perspectives with a high potential for growth in desiccant greenhouse technology.

The GCC countries must also address the need for greater research and a skilled workforce. Technological policies must be developed that focus on building a qualified workforce with specialized skills, and governmental and academic research institutions must be rebuilt. A permanent and interactive relationship is needed between the government, academic institutions and private sector entities on agricultural concerns. Establishing GCC cooperation in this area is important. It is also very important to involve the private sector in research activities and to encourage the sector to invest in these activities.

Leveraging important dimensions of technology to achieve sustainable agricultural development in the GCC region will require real efforts and cooperation by all Arab countries. Establishing solid technological relations with international technological and research pools is also important. Even with international support from countries outside the GCC, cooperation between the Arab nations is still necessary because research in other regions focuses on their own particular needs. Therefore, cooperation between Gulf and Arab countries is necessary to enhance research spending on crops of regional interest, as well as research on water use rationalisation and treatment technology, on generating new sources of fresh water and on protected agriculture technology, especially soilless agriculture and greenhouse design with low water-consuming cooling systems.

The GCC countries should promote a multilateral, common research agenda. Because many Arab countries share the same primary agricultural goal (food security) and challenges (water scarcity and climate change), a common multinational research agenda could benefit a greater number of people. ICARDA, FAO and ICBA have a mandate that covers most Arab countries. An independent Arab agriculture funding institution could work with these international centres, national research centres and other organizations to achieve shared objectives.

Capacity development programmes would benefit all the countries, enhancing the capacities of different stakeholders. Disseminating knowledge on greenhouse production systems, and increasing crop production and economic viability of investments is crucial for the adoption of new technologies. Stakeholders should be introduced to targeted technologies used in the context of protected agriculture that increase water use efficiency, productivity and profitability.

ICARDA and ICBA, in conjunction with national institutions and in cooperation with FAO, could support capacity building programmes on priority topics and covering technical as well as economic and environmental aspects for sustainable protected agriculture development in the GCC.

6.3 RESEARCH

Several greenhouse practices and technologies, such as fan and pad climate control systems, drip irrigation and hydroponics, have been used for the last 40 years, with little innovation, especially in climate control systems. In many regions of the world, greenhouse business developed well but also led to dramatic overuse of groundwater stocks.

In the Gulf region, such overuse has reduced groundwater levels and caused seawater intrusion, with a corresponding increase in salinity. The result is a growing dependency on state of the art desalination technologies such as reverse osmosis and multi-flash thermal distillation. These technologies, in turn, are increasing dependency on fossil energy sources like oil or gas, a process known as the energy-water nexus. Together with the use of desalinated water in irrigated agriculture, these elements are known as the energy-water-food nexus.

It is expected that the energy demand for desalination in the Gulf region, especially for reverse osmosis (the most energy-efficient solution), will gradually be met with renewable energies, such as wind power and photovoltaics, in order to provide a renewable and sustainable source of energy for the future provision of water and food.

Also, under investigation is the concept of solar thermal desalination, based on the solar still, with solar water heating and cooling using ambient air.

For the Gulf region, this solution is critical, considering the low potential of passive cooling at high ambient temperatures (for both daytime and night-time) as well as the high water temperatures in the Arabian Gulf.

In a normal solar still, the problem can easily be solved by increasing the temperature in the evaporation process, while in a greenhouse-integrated solar still, air temperatures are limited by the temperature requirements of the plants.

The overall water demand of irrigated agriculture, especially for evaporative cooling in greenhouses, is dramatic, and the use of desalinated water for this purpose, whether it is produced using fossil fuels, wind or solar power, is extremely expensive and may hardly be justified.

Based on these considerations, the agriculture sector requires a new approach, in which greenhouse climate control technologies are merged with solar water distillation. There is a great availability of seawater, solar radiation and desert land along the coastal areas of the region, namely along a 50-km strip around the Arabian Gulf. Of course, seawater cannot be used directly for irrigation. This may only be possible for a very small fraction of halophytic, salt-tolerant crops. However, water which evaporates from cooling pads can be a source of fresh water.

A new set of technologies seem to be on the horizon. These use seawater as the only remaining water source, or, where applicable, use seawater together with other alternative water sources, such as pretreated wastewater and harvested rainwater, for greenhouse agriculture. The basic principle of these technologies is to provide air with very high levels of humidity from the evapotranspiration of the greenhouse vegetation and seawater evaporation. Different technological approaches can be used to turn the water vapour back into sweet water. For this, a condensation process must be integrated into the greenhouse climate system. This can be considered for both open greenhouses, where water is condensed before the humid air leaves the greenhouse, and for closed growing environments.

Closed greenhouses have specific advantages for the Gulf region, as ambient air humidity is already very low, which is best for good cooling performance. One option is to use the internal air, dehumidify it, release the thermal energy involved in the latent heat of the phase change from vapour to water and, finally, re-humidify the air, allowing for further air cooling. In this process, the different day and night greenhouse temperatures would be a free source of coolness to drive condensation and obtain desalinated fresh water. Another advantage of closed greenhouses is the increased CO_2 in the air, allowing for increased growth of the vegetation. Increased productivity and sweet water production may offset the higher investment costs for this kind of climate control and water recovery technology.

Pretreated wastewater could also be considered for use in greenhouse production. This would increase overall water efficiency and water recovery and provide additional nutrients for the crops. If hygiene is an issue, it is still possible to grow non-food crops, such as crops used for textiles, paper production or construction. Furthermore, the condensed water obtained in greenhouses of this kind can be used for food crop production in nearby greenhouses.

If we imagine a seawater distribution system in the 50-km area along the Gulf coast, other technologies could be linked to this technological approach. For air conditioning of buildings – another high energy consumer – the evaporation of seawater could be used as a further source of coolness to enhance the resilience against climate change and particularly the prevailing high temperatures. Humid air released from the sea water-based cooling system could be directed into building integrated greenhouses on rooftops, on facades or in the neighbourhood. Here again, the water can be recovered and turned into sweet water as part of new urban climate control and water supply mechanisms.

The minerals contained in the brine produced from desalination could also be used as a resource. One cubic meter of seawater contains around one kilogram of magnesium chloride and one kilogram of potassium chloride. Together with the main constituent, sodium chloride, these minerals can be used as the base for different industrial products. Potassium, which can be extracted from seawater and the wastewater stream, is the third main mineral in plant nutrition and thus can also be used as a plant nutrient to complete the requirements for nitrogen, which can be extracted from the air.

Accumulating salt minerals in open desalination ponds may also contribute to decreasing the surface temperature. Thus, greenhouses and saline water ponds could contribute to improving climate conditions around cities.

It is too early to say which technology is the most suitable for the region, but the new technologies have very high potential to form the basis of sustainable life and sustainable economies in the Middle East. Only a few prototypes of greenhouses applying these new technologies have been approved around the world and they are not yet market-ready. There is a great need for more research, but it seems worthwhile to develop the technology, as it could provide a solution for the high and growing demand for renewable sources of water and food. If we imagine viable, economic greenhouse technologies producing water, food and renewable materials for the industrial sector, we can also imagine the Gulf region as a self-sustaining region with balanced food imports and exports.

Arab countries can develop innovative strategies that encourage private-sector investment in agricultural research and development. Since agricultural research produces mainly public goods, it is difficult to stimulate private investment.

Nevertheless, the investment climate can be strengthened in several ways, especially through stronger intellectual property rights for improved varieties and other innovations. In Latin America, competitive funding for research and development (R&D) has become common. Private firms are allowed to compete for public funds, which they can use for research, along with private co-financing. Another method is to offer rewards for certain innovations, such as drought-resistant wheat varieties, that are developed by the private sector. Still another method is to encourage innovation by making grants available to farmers to implement new technologies. This type of grassroots, farmer-led R&D has spurred technology dissemination and increased incomes in several countries (World Bank, 2008i). Ultimately, a partnership between public, private, and farmer-led research will be required to enhance R&D in Arab countries (World Bank, 2008e).

6.4 POLICIES AND INSTITUTIONAL REFORM

Arab countries, like many other countries in the world, suffer from a large gap between their food production and their food needs, especially basic food commodities such as cereals, oils, vegetables, fats, sugar and meat. In the GCC, several issues affect food security, including geographic and economic issues, and these must be considered in developing food security policies, at the country level and at the regional level. The region has some of the most extreme climate conditions in the world, as well as water scarcity, land degradation and desertification. These conditions should be the basis for determining trends and for policy formulation, especially regarding agriculture and food, and for developing food security programmes.

Joint action by the GCC countries in the field of agriculture and food production is based on the GCC Common Agricultural Policy, which aims to maximize the role of the private sector in carrying out the tasks of agricultural production and related production activities by providing institutional and structural support. The support encourages private initiatives in the modern production sector as well as initiatives to develop and modernize the traditional production sector. These tasks involve multiple interventions, which include the provision of infrastructure for all production stages.

The governments of the GCC countries support the agriculture sector and especially protected agriculture. For instance, enabling policy measures in the form of incentives for on-farm assets (irrigation equipment and greenhouses) have been implemented in the Bahrain, Oman, Qatar and United Arab Emirates (the).

GCC governments encourage farmers to adopt smart-farming practices, technologies and crops that are sustainable. Agricultural sustainability can be increased by selecting crops that do well with little water and by using more efficient methods such as hydroponics and drip irrigation (where every drop of water reaches the roots of a plant).

Strengthening farmers' technical capabilities ranks high as a priority. The Farmers' Services Centre (ADFSC), an Abu

Dhabi public organization established in 2009 to bring strategic agricultural reform to Abu Dhabi and to modernize farms in United Arab Emirates (the), has more than doubled the number of farms with water-saving irrigation systems through its efficient irrigation fund. To boost the horticultural sector, the ADFSC is establishing a centre of expertise, in collaboration with Netherlands (the). The ADFSC also provides technical and operational support services to farmers, helping them grow and market their produce.

Part of the ADFSC's mandate is to introduce and encourage the conservation of natural resources. Conservation is politically difficult, but it offers development opportunities to meet the country's growing demand. Over time, the region will rely increasingly on desalinated water, which is expensive and energy-intensive. But there is huge scope to make economies more water-efficient. At present, there are considerable inefficiencies all along the production, distribution and consumption chain, starting with energy-inefficient production and ending with water-inefficient consumption. Consumers, however, have little incentive to conserve water, as governments bear most of the cost of desalination.

Developing a vision for the future development of the agricultural sector and food production in the GCC states should be based on data regarding the current conditions of the natural resources and agricultural environments. Stakeholders must realize that achieving complete or partial self-sufficiency in food commodities is unrealistic, especially for basic crops that require large quantities of water or climatic conditions that are not available in the GCC. Although agricultural policies in some GCC countries have achieved quantitative targets in the production of some basic crops, the results of these policies show that this trend is no longer possible and that these policies must be changed. Considering the principle of comparative advantages, the GCC countries must make optimal use of their production resources (namely energy, labour and capital) and focus on the promising production sectors in which they have experience and have achieved high production rates, such as protected agriculture.

An important element in enabling the agricultural sector to adapt to socio-economic changes at the local and regional levels is to restructure rural development institutions, such as the ministries of agriculture. Improving the efficiency and effectiveness of such institutions and adjusting their roles will facilitate the design and implementation of appropriate agricultural development strategies and policies that will bolster the agricultural sector and the national economy. These policies and strategies must answer to the developmental needs and obstacles of the agriculture sector. Institutions, such as the ministries of agriculture, must be designed commensurate with the specific development needs of each country to ensure that they respond to current and future changes in socio-economic and environmental pressures (FAO, 2009).

Sustainable development requires new methods of policy decision-making. A more integrated and comprehensive approach to economic, social and environmental problems is needed to improve the framework in which decisions are made. This should include changing institutional and legal frameworks, developing integrated national strategies for sustainable development, capacity-building, and improving information systems in support of decision-making. Some related actions are described below.

- Need for a balance between water resources and the quantity of water consumption, to ensure a balance between water and food self-sufficiency. Plan the use of water, taking into consideration the cost of desalinisation and the availability of water, and working to create a strong community commitment to rationalising its use at all levels. Emphasise the best practices in rationalisation and use effective means to apply rationalisation methods, such as credit, water research, information and education.
- Establish an agency within the ministry of agriculture focused on water, to directly supervise and legislate on irrigation and drainage affairs, including laws aimed at reducing water depletion and increasing field irrigation efficiency and crop water use efficiency.
- Establish a financially and administratively independent financial support institution, headed by an expert in agricultural finance and credit, focused on developing, supporting and financing agriculture, food production and processing.
- Increase storage capacity and increase the size of the strategic stock of the main food commodities. There are many ideas in the Gulf on how to secure this stock. One option under consideration in United Arab Emirates (the) is to allocate land to establish greenhouses for food crops through the private sector. Another option is to call on experts of participatory interventions and consumer protection to establish a government institution to secure strategic food stocks. This would help stop or mitigate the rise in food prices.
- Provide institutional and structural support to the private sector in agricultural production and associated activities (such as the agricultural input industry and marketing and manufacturing of agricultural products) to encourage private initiatives in the modern production sector and help develop and modernise the traditional production sector.
- Support applied agricultural studies and research.
- Expand cooperation between research centres, universities and institutes in the GCC.
- Provide an online database on water, irrigation, drainage and crop water needs so that farmers have the necessary information to schedule irrigation according to climate, soil and crop data.
- Expand the provision of renewable water resources such as treated wastewater, salt water and agricultural drainage water and increase water-saving practices and infrastructures such as rainwater harvesting and dams.
- Enact regulations on watered fields to limit water loss, such as requiring the installation of water meters, with appropriate pricing for those whose consumption exceeds the water requirements of crops.

Improving the productivity of existing irrigation networks is a key element of agricultural modernization in the GCC. A few untapped opportunities still exist in this regard (FAO, 2009):

- A mix of regulations and subsidies can be used to encourage the shift from flood irrigation, which is still widely practised, to modern techniques such as drip irrigation. Localised irrigation allows water to reach the roots of the plants directly through pipes and valves, thus saving water and minimising soil erosion and the use of fertilisers.
- Regulations can be used to recover water costs from farmers by pulling back subsidies on well drilling and through effective metering and billing at point-of-use. Once farmers start paying for the water they draw, they are likely to use it more efficiently and shift farm production to high-value crops (such as vegetables under protected agriculture) that allow them to recover their water costs.
- Subsidies can be partially reallocated to reduce the cost of importing and using water conservation technologies such as drip and sprinkler irrigation, moisture sensing, water use metering, etc. Subsidies can also be provided in the form of cheaper and more accessible credit for the purchase of such equipment and the provision of technical consultancy for installing these modern systems.

At the regional level, cooperation between the GCC nations and between the GCC and other Arab countries is needed in order to achieve the highest possible levels of self-sufficiency, based on the principle of comparative advantages in agricultural production. A specialized, financially and administratively independent institution should be established with branches created in each of the GCC countries. Through these branches, a committee will study the current food needs and anticipate future needs in order to develop strategies, plans and programmes to import food products and to adopt import systems to avoid crises and bottlenecks, which often occur because imports are sourced from a limited number of countries. If it is necessary to import, then this should be done in accordance with clear economic agreements in order to avoid, whenever possible, any crisis or interruption in supplies that could endanger the food security of the GCC countries.

The creation of such an institution would provide greater negotiating capabilities in the agricultural and food commodity markets. It would regulate import operations according to a clearly defined timetable, taking into consideration the global movement of food commodities in the international stock exchanges and markets when making current transactions and futures contracts. The institution would also regulate and manage a strategic stock of agricultural and food commodities and inputs, acquired at the best prices, for the GCC states, as well as the necessary infrastructure.

6.5 ACCESS TO EXTENSION SERVICES

Arab countries must couple research and development investments with better extension. Agricultural extension in the GCC countries is poor. A successful extension programme must reach large and small farmers alike. Large farmers have the greatest productive potential per farmer and the ability to invest in relatively expensive new technologies. Smallholders produce less food per hectare and per farmer but make up a large proportion of the target population of extension services. The biggest failure of agricultural extension has been the failure to provide smallholders with basic information (Gana *et al.*, 2008). Smallholders often struggle to compete because they lack basic technical and marketing information. They require support from extension services to produce and market crops and to generate economic opportunities through value addition and other means.

According to the World Bank (2009):

Household assets, land, physical capital, education and health are crucial factors in the ability of farmers to secure rural livelihoods and to participate and compete in agricultural markets (World Bank, 2008e). Enhancing access to these assets is critical to improving purchasing power and will require significant public investment.

A range of options could be used: developing rural infrastructure, improving product markets and access to financial services, strengthening producer organizations, and arranging payments for environmental services.

Facilitating access to and adoption of innovative technologies by small-scale farmers deserves increased attention. This will be crucial to ensure the competitiveness of the small-scale farming sector.

6.6 PUBLIC AND PRIVATE INVESTMENTS IN AGRICULTURE

As part of the food security strategy, in recent years, fiscally strong governments and agricultural corporations have increasingly begun to invest in land abroad. The GCC governments have become important participants in this process. Investments in foreign farmland are now increasingly being shaped by governments rather than corporate players, which in the past sought to benefit from lower production costs in developing nations. The role of the public sector is growing through direct investment and investment by state-sponsored entities or public-private partnerships, such as the King Abdullah Initiative for Saudi Agricultural Investment Abroad. With the nature of investors changing, the motive of land acquisition is also evolving from profit to food/energy security. Correspondingly, the mix of target crops has begun to shift away from cash crops such as bananas, coffee, and tea toward staples and biofuels such as wheat, maize, rice, and jatropha.

The GCC countries have been investing primarily in North-eastern Africa and South Asia (Economist Intelligence Unit, 2014). Instead of looking to invest in major exporting nations and regions such as the United States of America, the European Union and Australia, the GCC nations have tended to focus on countries that are geographically close and have established ties to the GCC. Pakistan and Sudan in particular have figured prominently in connection with these efforts. Some Arab countries with investable capital have outsourced food production abroad, to countries endowed with abundant land and water resources. Bahrain, Egypt, Jordan, Kuwait, Libya, Qatar, Saudi Arabia and United Arab Emirates (the) have already acquired land in other Arab states and in Africa. The land area acquired by these countries amounts to 7.462 million ha and will be used for the production of various crops, including wheat, rice and maize (UNEP, 2011).

The underdeveloped agricultural sectors of these countries have room for yield improvement, while their geographic proximity helps keep transportation costs in check. The established political and cultural ties are seen as a safeguard against the risk of embargoes. Saudi Arabia and United Arab Emirates (the) have now emerged as leaders in acquiring land in third countries with media reports suggesting that, together, they hold 2.8 million ha, primarily in Indonesia, Pakistan, Sudan and Turkey. Saudi officials have also reportedly had talks regarding investing in Australia, Brazil, Egypt, Ethiopia, Kazakhstan, South Africa and Vietnam. The GCC nations are not only investing directly but are also supporting the private sector in acquiring land overseas. A private Saudi firm, Planet Food World (PFWC), is reportedly planning to invest around USD 3 billion in Turkey's agriculture sector with the goal of exporting farm products back to the GCC. PFWC is planning to build around 20 000 farms with an average area of 10 000 square meters each to cultivate vegetables and fruits and to raise cattle, poultry and sheep. PFWC has also invested in Ethiopia. Another company, Hail Agricultural Development Company (HADCO), formerly a listed company but acquired by Almarai in 2009, recently acquired around 8 900 ha of land in Sudan on a 48-year lease. HADCO is planning to invest in Kazakhstan and Turkey as well.

South Africa is also targeted for investments since it has great agricultural potential. Of the 122 million ha total land surface, South Africa has cultivated only 10 million ha.

Other countries in Africa also have considerable potential. They are Libya, Madagascar, Mozambique, United Republic of Tanzania (the) and Zambia, all of which have large tracts of underutilised arable land and are close to Middle Eastern markets. Libya also has large underground water sources and the remaining countries have large supplies of irrigation water at low pump head from rivers.

Despite the low added value of agricultural products, the agriculture sector's social and political importance remains considerable, not least because of food price pressures. Food consumption, especially of high-value products such as fruit, vegetables, meat and dairy, is growing as the population base expands, urbanization rates increase, and disposable incomes grow. The food price shock of 2008 was a salient case in point, made worse by the broader backdrop of accelerating inflation. The limited monetary policy autonomy of the regional central banks, due to the U.S. dollar pegs, created considerable challenges for policymakers who were forced to resort to a combination of short-term measures with relatively modest impacts. Faced with simultaneous pressures of rising demand, falling domestic agricultural yields and the apparently long-term trend of global food price inflation, the GCC nations require comprehensive food security plans.

Agricultural investment by the GCC countries in other Arab and foreign countries as a strategic option for securing GCC food supplies requires:

- a comprehensive survey of countries with natural agricultural resources and an investment climate that allows for investment in the agriculture sector, including the possibility of reclaiming arable land in those countries;
- drafting a model framework agreement on joint foreign investments by the GCC states or investments by individual GCC countries in the field of agriculture.

Framework agreements on such investments should be sovereign, not subject to changes within the state, and should emerge from political ties between countries, to ensure the stability and sustainability of joint agricultural investments. Liaison centres should be established within each GCC country to facilitate procedures, activate agreements and preserve the rights of investors.

The framework agreements should encourage private enterprises to enter the field of agricultural investment and assume its risks through a package of incentives, procedures and guarantees. These packages would protect the investments and allow the private companies to benefit from government support of farmers within their territory, including credit, subsidies, crop purchase, export insurance, transportation, etc.

There are many initiatives already in process, including the call for the private sector to establish large, joint Gulf companies to invest in agriculture. Another initiative is to allocate lands in Arab agricultural countries, such as Sudan, or in European or Asian countries, for agricultural investment by Gulf companies, which would be established in those countries to own and operate the agricultural operations. With proper political support, legal frameworks and clear agreements, these operations could satisfy part of the needs of the domestic market.

Government support and financial incentives in the GCC have encouraged private participation in the agriculture sector. The Saudi government has simplified the previously bureaucratic process of investment by private domestic and foreign players and is offering financial incentives. The government is also building infrastructure to boost the attractiveness of the sector. Saudi Arabia also plans to establish new desalination plants and upgrade the existing ones. Similarly, Qatar has allowed 100 percent foreign ownership in agriculture and reduced the corporate tax from 35 percent to a flat 10 percent. Private players can introduce modern technology in the form of water management products and advanced irrigation equipment and can also help introduce new seeds for high-yield, low water consuming plants.

Private participation in the agriculture sector in Oman and Bahrain is 68 and 40 percent, respectively, all in small-scale farming. In Saudi Arabia, private participation in the agriculture sector is 37 percent (Table 6.1).

Table 6.1 Private participation in GCC agriculture sector

	Bahrain	Kuwait	Oman	Qatar	Saudi Arabia	United Arab Emirates
Small-scale farm holdings by area	68%	N/A	40%	27%	37%	N/A
Number of companies in agriculture sector	N/A	11	8	2	48	14
By activity:						
Crop and animal production	N/A	8	2	2	34	5
Agriculture services	N/A	3	6	0	14	9
By ownership:						
Publicly listed	N/A	4	1	0	10	1
Privately held	N/A	6	7	1	36	11
Government entities	N/A	1	0	1	2	2

Source: *FAO, 2009.*

The main forms of agricultural support to the farmers in the GCC include (FAO, 2009):

- Free mining of groundwater (though Oman regulates new well digging).
- Farms, seeds, fertilisers and other inputs are provided free of cost or at subsidised rates. For example, Saudi Arabia provides farmland free of cost, while Qatar subsidises between 25 and 75 percent of the cost of land levelling, seeds, fertilisers and cultivation. United Arab Emirates (the) provides half the cost for crop protection, veterinary services and other inputs, such as fertilisers.
- Individual governments conduct research, provide technical support to farmers for cultivation, irrigation and other agricultural activities, and undertake public warehousing to improve food security.
- Price support has also long been used in the GCC to make agriculture attractive to farmers, despite the high production costs in the region. Saudi Arabia, for example, established guaranteed prices for wheat and other cereals (which it is now phasing out), while United Arab Emirates (the) purchases dates and fodder in some emirates.
- In some cases, countries have provided indirect support to private companies engaged in agriculture. This is the case of Qatar, which has lowered taxes for private agricultural companies.

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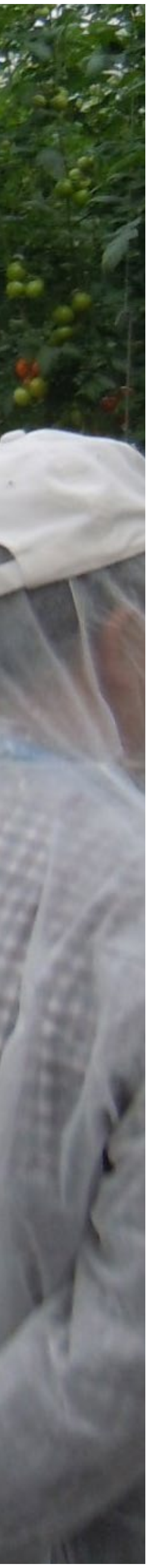

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ANNEX 1
PROTECTED AGRICULTURE IN THE GULF COOPERATION COUNCIL COUNTRIES

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PROTECTED AGRICULTURE IN THE GULF COOPERATION COUNCIL COUNTRIES

PROTECTED AGRICULTURE IN BAHRAIN

The first greenhouse used in vegetable production in Bahrain was introduced at the Ministry of Commerce and Agriculture Research Station in Budiya, in 1976. This low-cost, single-span low tunnel, non-cooled plastic greenhouse measured 4 x 50 m and was 3 m high. Only three years later, almost 59.5 ha of farmland were under protected agriculture. The introduction of new methods of modern water-saving irrigation systems, like drip irrigation, made the adoption of protected agriculture among farmers a lot easier. In the mid-1980s, the government started the protected agriculture subsidy programme to encourage them to initiate or expand protected agriculture systems. Through the programme, greenhouse structures, covers, fertilizers, seeds, integrated pest management tools and hybrid seeds were made available to the farmers at highly subsidised rates. Greenhouse production is ideal for the status of natural resources in Bahrain. Its ability to produce more in limited areas with minimal water was behind the spread of protected agriculture among farmers. By producing in greenhouses, farmers were able to save at least 50 percent of irrigation water compared to open-field production. A further 35 percent of water was then saved when soilless culture (especially closed-system hydroponics) was adopted. By the end of the 1990s, protected agriculture was extremely popular among Bahraini farmers. This is shown in Figure 1 below. Today, almost half of Bahrain's farmers produce in more than 4 000 greenhouses, with a total area of 85 ha. Moreover, four commercial greenhouse growers have recently established their farms in the country.

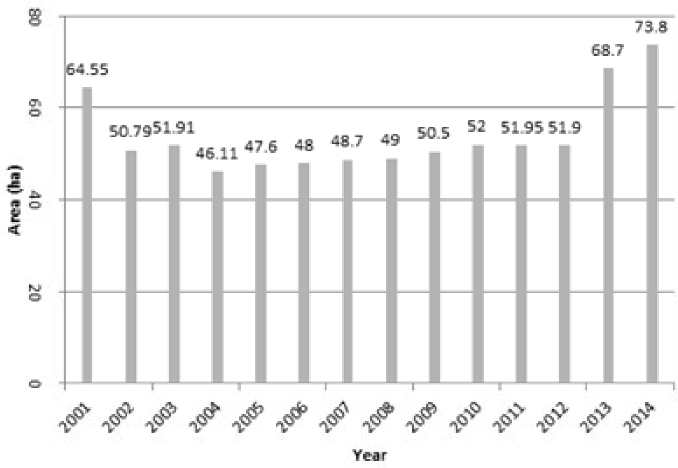

Figure 1. Development of protected agriculture in Bahrain from 2001 to 2014

Source: *Abdulrazak, 2014.*

Greenhouse design

Bahrain benefitted greatly from the Arabian Peninsula Regional Program (APRP). Greenhouse structures were significantly improved over time, as follows:

- Low tunnel units (4 m x 50 m x 3 m) were replaced first by single-span plastic greenhouses (6 m x 42 m). This allowed for an extra two rows of plants. Later, wider greenhouses (9.4 m x 42 m x 4.5 m) were introduced, which allowed for two additional rows of plants.
- The height of the greenhouses was increased to 4.3 m (inside the arch). This allowed hot air to move up and away from the crop canopy. At the same time, the ventilation opening was designed and placed in a zigzag pattern on the sides of the greenhouse to increase passive air replacement and movement across the length of the greenhouse.
- Half-moon-shaped greenhouses were then replaced by Gothic-shaped greenhouses with even higher structures (4.5 to 5.0 m). This allowed for more efficient land use, especially along the sides of the greenhouses.
- Evaporative cooling systems were introduced to extend the growing season inside the greenhouse. At first, there was concern regarding the economics of the system and whether the additional production would justify the investment. The length of the cooled greenhouse was reduced to a maximum of 36 m. This was necessary to reduce temperature differences along the greenhouse.
- A range of experiments and trials were then carried out to compare different types of greenhouse covers. Plastic film, corrugated fibreglass and polycarbonate were tested. Besides the technical characteristics of each material, its cost, durability, lifespan and light transparency were studied.
- Towards the early 1990s, double and multi-span greenhouses were introduced to meet expanding requirements to produce in larger protected areas.
- Bahrain led the way conducting trials to improve the evaporative cooling efficiency by introducing several measures to enhance the greenhouse environment. The use of reflective aluminium striped covers, roof ventilation and perforated roof pipes, among other measures, were introduced to farmers. Major projects were implemented to improve greenhouse design for better cooling and water savings. One such project was the construction of a set of round, connected greenhouses, which were intended to circulate cooled air and at the same time harvest water from the rising humidity inside the structure.

Soilless systems

Due to problems of soil-borne diseases and the salinity of agricultural lands, soilless culture was introduced around 2004. It proved very successful, with excellent results in yields per unit area and water efficiency. The amount of water required for irrigation was also considerably reduced. The use of different integrated production and protection management (IPPM) tools, which reduced the use of chemical pesticides and insecticides, was positively reflected in product quality.

Production in greenhouses had opened the farmers' vision to introducing different growing systems. Growing in pots, plastic tunnels, pipes and brick channels were among the many applications local farmers adopted to maximize their production and lower their initial investment. Soilless systems also made it possible for greenhouse growers to expand production inside greenhouses vertically. Strawberry, lettuce and dwarf bean crops were grown in a vertical hydroponic greenhouse system called stackers.

Plans to promote protected agriculture in Bahrain

The following topics need to be tackled to make protected agriculture even more performant:

- test new growing systems and substrates made from local materials;
- promote and support expansion of soilless culture to save water and increase yields per litre of water;
- introduce renewable energy applications (solar) for environmentally friendly, sustainable production;
- set standards and create protected agriculture manuals with specifications to suit Bahrain's climate conditions;
- encourage agro-entrepreneurs to establish high-tech protected agriculture projects through the recently established Bahraini agricultural growth poles (Bahrain Agricultural Incubator).

Main players in agricultural development in Bahrain

- Ministry of Works, Municipalities Affairs and Urban Planning
- Arabian Gulf University

PROTECTED AGRICULTURE IN KUWAIT

Due to harsh climate conditions in Kuwait, most farmers have turned to greenhouse production rather than open-field production to avoid the harmful effects on crops of the high temperatures, winds and the lack of moisture.

Depending on the season, the distribution of numbers of greenhouses cultivated varies according to the covering material. Polyethylene remains the dominant covering material in all seasons. The number of greenhouses covered with shade nets remains almost constant, whereas the number of greenhouses cultivated with rigid covers (fibreglass and glass), decreases in late summer. In general, the number of cultivated greenhouses, irrespective of the cover type, decreases as the outside temperature increases with the season from winter to late summer.

Table 1 Number and types of greenhouse covers by season in Kuwait, 2013/2014 season

	Type of greenhouse cover				
Season	Polyethylene	Net	Fibreglass	Glass	Total number of greenhouses
Winter	11 280	486	802	99	12 667
Early summer	5 816	486	867	56	7 225
Late summer	4 432	432	287	30	5 181

Source: *Central Statistical Bureau of Kuwait, 2014.*

Table 2 Greenhouse area

Growing season	2007/08	2008/09	2009/10	2010/11	2011/12
Area (ha)	1 169.9	1 204.8.7	1 271.9	1 469	1 567.9

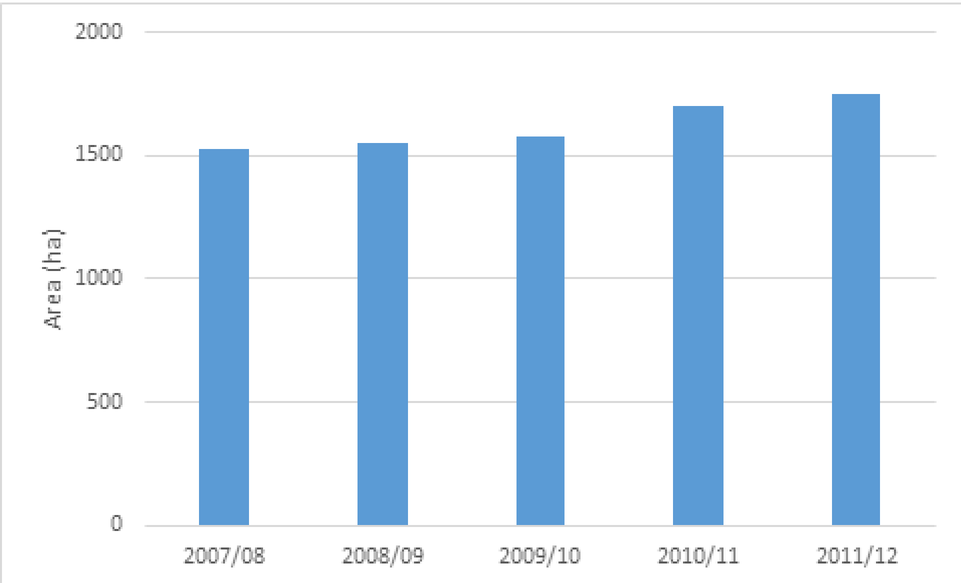

Figure 2 Status of greenhouse cultivation in Kuwait

Source: *Central Statistical Bureau of Kuwait, 2012.*

The Public Authority of Agriculture and Fish Resources (PAAFR) encourages the expansion of greenhouse production through the following measures:

- At least 20 percent of the total area of all farms must be under greenhouse production.
- Direct subsidies are provided to growers by the government through the PAAFR.
- Training, technical advice and seminars are provided to farmers.
- There is extensive collaboration with international and regional organisations (ICARDA, FAO, Kuwait Foundation for the Advancement of Sciences, Kuwait Institute for Scientific Research, Kuwait Fund for Arab Economic Development, King Faisal Foundation and Supreme Council for Planning and Development) to carry out activities that benefit growers.

PAAFR also issues technical greenhouse specifications that every farmer should comply with. Greenhouse and farm plans must be approved by PAARF before construction.

In Kuwait, the cultivation of fruit vegetables is the dominant category, regardless of the greenhouse cover material, followed by leafy vegetables and pulses.

Table 3 Cropped area of protected crops according to the crop categories cover material, 2014/2015 (1 000 square meter)

Crop	TOTAL	Glass	Fiberglass	Roclaine	Polyethylene
Total fruit vegetables	15 473	89	997	87	14 300
Total leafy vegetables	2 873	24	192	124	2 533
Total tubers and bulbs	190	0	13	7	170
Total pulses	1 149	2	44	0	1 103
Total cereals	34	0	0	0	34
Total green fodder	0	0	0	0	0
Total cropped area	19 719	115	1 246	218	18 140

Source: *Central Statistical Bureau of Kuwait, 2015.*

Drip irrigation is the main irrigation modality in all seasons. Other irrigation practices, such as surface or gravity irrigation, are marginal.

Table 4 Irrigation modalities according to season in Kuwait – Number of greenhouses in 2013/2014 season

Type of irrigation round	Drip irrigation	Surface irrigation	Other irrigation
Winter	2 120	440	19
Early summer	6 796	429	6
Late summer	4 488	302	14

Source: *Central Statistical Bureau of Kuwait, 2014.*

The largest quantities harvested are in the fruit vegetable category, followed by leafy vegetables and pulses. This is in line with the importance of the greenhouse area dedicated to the cultivation of each of these crops.

Table 5 Total harvest in tons/ha by groups of crops (2011-2012)

Crop	Greenhouse production (quantity)
Fruit vegetables	126 640
Leafy vegetables	16 101
Tubers and bulbs	1 254
Pulses	2 976
Cereals	170

Source: *Central Statistical Bureau of Kuwait, 2012.*

Main players in agricultural development

- Public Authority for Agricultural Affairs and Fish Resources (PAAFR)
- Kuwait Institute for Scientific Research (KISR)
- Kuwait University (KU)

PROTECTED AGRICULTURE IN OMAN

In the mid-1980s, new technology, known as protected agriculture, was applied by some major agricultural companies in Oman to fill the gap in vegetable production and increase productivity per unit area. Meanwhile, the Ministry of Agriculture and Fisheries (MAF) focused on rationalizing the use of irrigation water in agriculture through the adoption of new irrigation technologies for various vegetable crops and by increasing water use efficiency. Protected agriculture has proven to be adequate for growing high-value crops, such as cucumbers, sweet peppers and tomatoes. Figure 3 shows the number of subsidised and non-subsidised greenhouses in the country in 2014 (MAF, 2015).

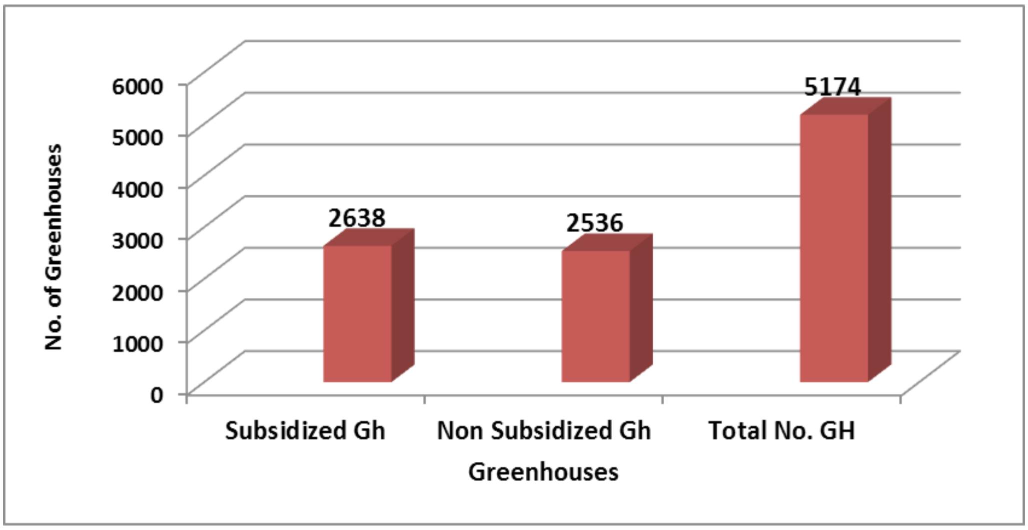

Figure 3 Subsidised, non-subsidised and total greenhouses in 2014

Source: *Ministry of Agriculture and Fisheries, 2014.*

In 2014, the total number of greenhouses (both soil and soilless systems) and shade nethouses was about 5 174 and 417, respectively (see figures 4 and 5).

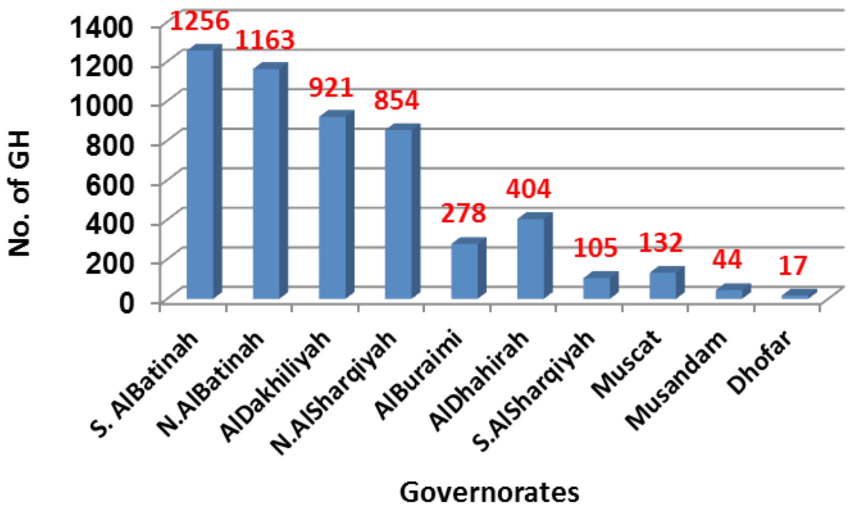

Figure 4 Number of greenhouses in different governorates in 2014

Source: *MAF, 2014.*

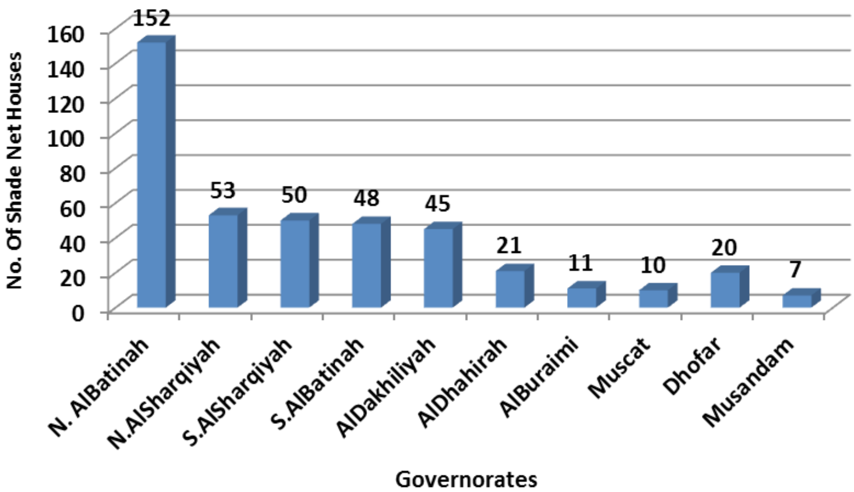

Figure 5 Number of shade nethouses in different governorates in 2014

Source: *MAF, 2014.*

Soilless systems

Soilless growing techniques are considered an important technology and appropriate for Oman due to the limited availability of suitable natural resources for favourable plant growth (soil type and availability of irrigation water). Soilless production was first introduced and adapted through agricultural research conducted at Rumais in 2000, in collaboration with the International Center for Agricultural Research in the Dry Areas (ICARDA). After its success and the simplification of the technology, it was disseminated to numerous farmers in different governorates. Figure 6 shows the number of greenhouses with soilless growing techniques (both closed and open systems) through December 2014 (MAF, 2014). However, many new greenhouses have since been established by the farmers, which are not included in the figure. The Ministry of Agriculture and Fisheries has initiated special programmes to encourage farmers to adopt soilless production through international programmes such as ICARDA's APRP, which is still being implemented. At the end of 2014, a multinational company (Haya for Agriculture Production), established multi-span soilless greenhouses covering around 33 000 feddans (13 860 ha) for the production of vegetables, such as tomatoes and capsicum. Each multi-span greenhouse covered about 5 000 m^2.

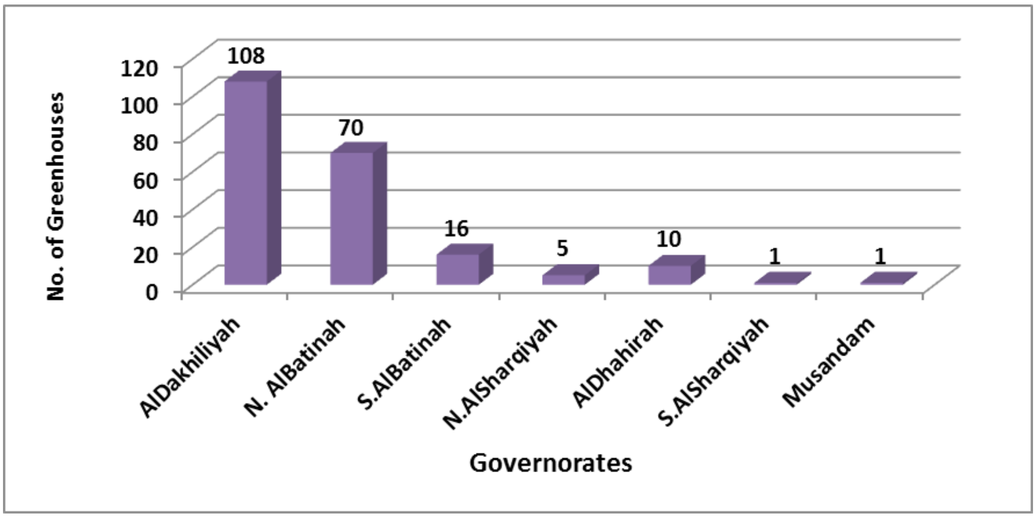

Figure 6 Number of soilless system greenhouses in different governorates in 2014

Source: *MAF, 2014.*

The role of agricultural research in the development of protected agriculture

Agricultural research played an active and important role in the development of greenhouses, in terms of improving their structure based on the requirements of Oman's edaphic and climatic conditions. Several experiments were carried out since the adoption of the greenhouse improvements in Oman. For instance, greenhouse length was changed from 40 m to 30 to 36 m, and the polyethylene plastic sheet was changed from a double layer to a single layer. The results of experiments with these modifications showed that the use of a single layer polyethylene plastic sheet produced a higher yield, with an increase of about 40 percent in production, and additional savings in other areas. The experiment also showed that reducing the number of irrigation lines from 6 to 5, resulted in higher productivity and less diseases. Double doors at the main entrance of the greenhouses were introduced and protective insect netting was installed on the cooling pads to reduce the use of pesticides. Together, these changes reduced the use of pesticides and increased cucumber yield.

In order to further develop greenhouse production, the Ministry of Agriculture and Fisheries, represented by the Directorate General of Agriculture and Livestock Research, participated in the Arabian Peninsula Research Program, under ICARDA. This programme aimed to develop agricultural research in Oman in three components: genetic resources, water and protected agriculture.

Main players in agricultural development

- Ministry of Agriculture and Fisheries (MAF)
- Muscat Overseas Group
- Sultan Qaboos University

PROTECTED AGRICULTURE IN QATAR

The State of Qatar has a great interest in developing the agriculture sector to achieve a high degree of self-sufficiency and fulfil the recommendations of its National Food Security Program (NFSP), which is in line with Qatar Vision 2030. The Ministry of Municipality and Environment is active in developing plans and programs for optimal utilization of available resources in the production of the most important crops. It has put forward development strategies for the agriculture sector and is supporting the implementation of different programs and developmental projects.

The National Food Security Programme (NFSP) adopted an agricultural strategy for local production that can be summarized in the following elements:

- develop sustainable domestic agriculture practices to mitigate the food security risk;
- develop low-input, environmentally sensitive and high-performing farming practices with minimum human workforce;
- produce agricultural products locally that cannot be stored for long time.
- establish food safety through a traceability system for vegetables;
- enhance sustainability (eco-friendly production practices).

Based on this strategy, the government encouraged the development of protected agriculture by subsidizing the establishment of new greenhouses, through extensive research on protected agriculture and through joint ventures between government-owned farms and international companies to establish greenhouses suitable for Qatari conditions. As a result of these efforts, the area and production under protected agriculture increased (Table 6).

Table 6 Cropped area and production of crops in greenhouses during 2015 – 2017

Crops	Year 2015		Year 2016		Year 2017	
	Area (Hectare)	Production (Ton)	Area (Hectare)	Production (Ton)	Area (Hectare)	Production (Ton)
Tomatoes	46.5	6513.6	39.289	5500.46	49.8	6977.9
Sweet pepper	15.84	791.9	19.691	984.57	19.8	989.4
Melon	5.5	437.1	4.003	320.256	3.6	484.5
Cucumber	113.2	11319.5	130.168	13016.83	119.4	11939.2
Beans	22.9	913.9	23.350	934.012	27.8	1113.5
Other vegetables	30.6	1261.2	27.5	1106.5	29.2	1169.8
Total	**5 .234**	**21237.3**	**244**	**21862.604**	**249.7**	**22474.3**

Source: *Ministry of Environment, 2017.*

Overall, as of 2017, protected agriculture in Qatar does not exceed 2.2 percent of total cultivated area, with cucumber comprising almost half (47.8 percent) of the protected area followed by tomato, at 20 percent (Figure 7).

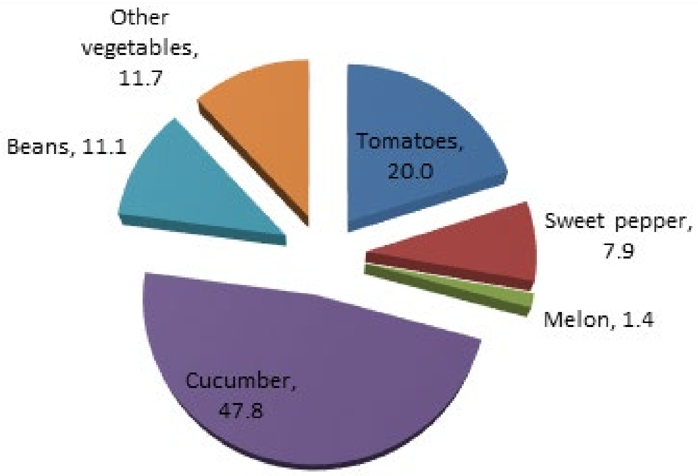

Figure 7 The proportion area covered with major vegetables in protected agriculture in Qatar in 2017

Source: *Annual Bulletin for areas and crop production 2017, Ministry of Environment 2017.*

Different types of greenhouses have been established in Qatar, and different cultural practices are being used, as shown in Table 7.

Table 7 Different types of protected agriculture in Qatar

	Non-cooled greenhouses		Cooled greenhouses		
	Screen-house	**Greenhouse**	**Single-arch**	**Multi-span**	**Others**
Covers	Insect-proof net	Polyethylene	Polyethylene	Polyethylene Fibreglass Polycarbonate	Polyethylene Polycarbonate Glass
Height (m)	3.2	3.2	3.2	4–6	4–8
Length (m)	39	39	20–35	Variable	Variable
Width (m)	9	9	9	20–36	Variable
Cooling system	None	None	Evaporative cooling system (ECS)(Cooling pads and fans)	ECS	ECS Air conditioning (AC) Hybrid (ECS-AC)
Culture media	Soil	Soil	Soil	Soil Growing bags Hydroponics	Soil Growing bags Hydroponics
Main crops	Tomato Cucumber Eggplants Okra Sweet melon Sweet pepper	Tomato Cucumber Sweet pepper	Tomato Cucumber Green beans Sweet melon Sweet pepper	Vegetables Ornamental plants	Vegetables Ornamental plants
Growing season (month/year)	7–8	5–6	9–10	9–10	10–12

Source: *Annual Bulletin for areas and crop production 2017, Ministry of Environment 2017.*

The blockade of 2017 had a positive impact on the growth of the greenhouses and greenhouse production area, as recorded during the winter months. The total number of cooled and non-cooled greenhouses increased by 21.86 percent and 95.12 percent, respectively, while the total area under non-cooled and cooled greenhouse production increased by 10 percent and 46 percent, respectively. A slight increment of 2.43 percent was recorded for the hydroponic area under the cooled greenhouse production (Table 8).

Table 8 The increment of the area under greenhouse after the blockade of 2017 (data of winter months)

	Number	Area (ha)		Total area (ha)
		soil	hydroponic	
Non-cooled greenhouses				
2016-2017	2408	198.42	1.58	200
2017-2018	4153	218.42	1.58	220
Differences	745	20	0	20
%increment	21.86	10.08	0.00	10.00
Cooled greenhouses				
2016-2017	471	29.1	20.6	49.7
2017-2018	919	51.8	21.1	72.9
Differences	448	22.7	0.5	23.2
%increment	95.12	78.01	2.43	46.68

Source: *Annual Bulletin for areas and crop production 2017, Ministry of Environment 2017.*

Main players of agriculture development

- Ministry of Municipality and Environment (MME)
- Qatar University

PROTECTED AGRICULTURE IN SAUDI ARABIA

In the past few years, crop production is stagnating and is losing ground in respect to imports. Large-scale crops produced in the country are effectively limited to cereals, vegetables, potatoes and dates. Lack of constant water sources and lack of arable land are the two major constraints facing sustainable agricultural development in Saudi Arabia.

Despite this, the country's food production is strong enough to meet a large part of its demand, maintaining a self-sufficiency ratio of 83.6 percent. The government supports the growth of high-value crops grown with the most sustainable techniques, such as protected agriculture. Since 1968, when the first greenhouse project was established in Riyadh, with a production capacity of 1 400 tons, many greenhouse projects have been set up throughout the country. In 2013, the estimated greenhouse area was 7 928 ha, with production at around 670 000 tons.

In terms of performance, greenhouses can be divided into two types, tunnel systems (non-air-conditioned) and pad and fan systems (air-conditioned). Both types have proved to be suitable for the climate conditions of Saudi Arabia. The tunnel system is used only in the winter to protect the crops from cool and potential freezing temperatures during the night, while the pad and fan system is used at most times of the year. The tunnel system predominates in the country, with an estimated 58 707 tunnel production systems, while there are an estimated 7 722 pad and fan systems (Figure 8).

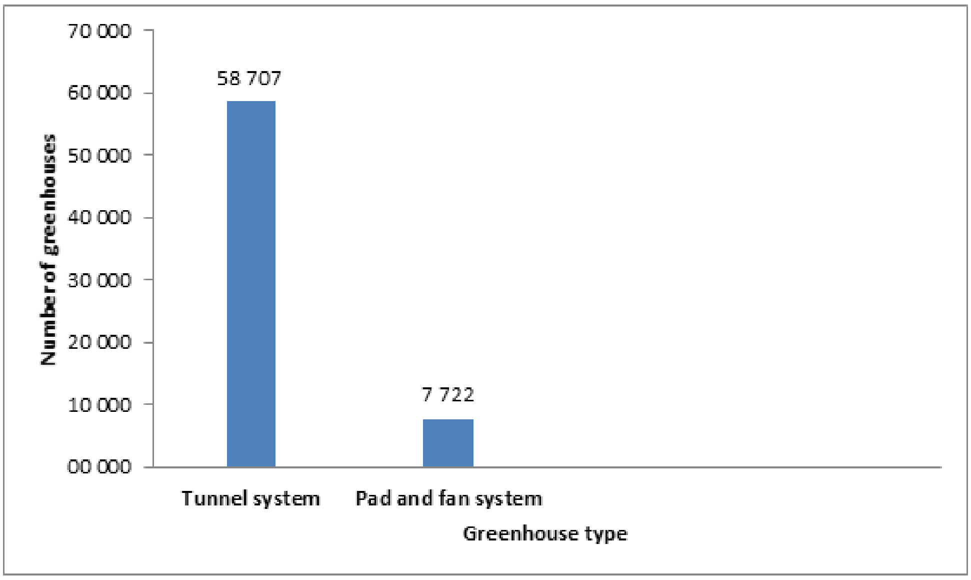

Figure 8 Greenhouses types and quantity in Saudi Arabia

Source: *Ministry of Agriculture, 2014.*

There are four types of greenhouse covers using pad and fan systems, the most widespread being plastic-covered greenhouses (Table 9).

Table 9 Number of pad and fan greenhouses in Saudi Arabia, according the cover material

Cover material	Number of pad and fan greenhouses
Plastic	6 207
Fibreglass	952
Glass	339
Polycarbonate	224

Source: *Ministry of Agriculture, 2014.*

The main crops grown in greenhouses are tomato (38.1 percent), cucumber (29.3 percent), sweet pepper (9.1 percent), eggplant (8.3 percent) and squash (50.5 percent).

Table 10 Greenhouse crops and area during the 2013 growing season

Crop	Production (tons)	Area (ha)
Tomatoes	320 215	3 947
Cucumber	236 087	2 605
Squash	15 309	189
Others	98 387	1 187

Source: *Ministry of Agriculture, 2014.*

Because of the high temperatures in most parts of Saudi Arabia from May to September, three factors negatively affect plant growth in greenhouses:

- hot air surrounding greenhouse when the outside temperature exceeds 45 °C;
- air distribution inside the greenhouse, which results in the temperature increasing one to two degrees from the pads to the fans (one degree every ten meters);
- heat near the roof because of the sun's radiation.

To study these difficulties, the Ministry of Environment, Water and Agriculture (MEWA) established a new research centre in Riyadh, the Sustainable Agriculture Research Centre (still under construction). The purpose of the centre is to conduct applied research on innovative techniques for greenhouse design suitable to the local conditions (including water use efficiency) and on the application of IPM for food quality and safety in protected cultivation.

Main players of agricultural development

- Ministry of Agriculture (MoA)
- Agricultural Information Centre (AIC)
- King Saud University (KSU)
- Saudi Basic Industries Corporation (SABIC)
- Grain Silos and Flour Mills Organisation (GSFMO)
- Almarai
- Savola Group
- Saudi Organic Farming Association (SOFA)
- Al Watania Poultry
- Arabian Agricultural Services Company (ARASCO)
- King Abdulaziz City for Science and Technology (KACST)
- King Abdullah University of Science and Technology (KAUST)

PROTECTED AGRICULTURE IN THE UNITED ARAB EMIRATES

Protected agriculture started more than ten years ago in United Arab Emirates (the). It has considerable potential and is viewed as a viable technology to attain a satisfactory degree of self-sufficiency in vegetable production. The government's policy encouraged the expansion of protected agriculture to improve agricultural production under conditions of water scarcity. The limited availability of fresh water resources in United Arab Emirates (the) makes it necessary to adopt strategies that help to reduce water use in agriculture or make the most efficient use of water. In this respect, protected agriculture, particularly for growing high-value crops such as vegetables, has significant potential.

The total planted area using protected agriculture technologies for the period 2007–2009 ranged between 5 388 dunums (538.8 ha) in 2007 to 3 721 dunums (372.1 ha) in 2009, with more than 70 percent of the greenhouses located in Abu Dhabi Emirate (Figure 9). The total number of greenhouses in United Arab Emirates (the) is about 19 000, of which 15 340 are in Abu Dhabi Emirate and about 3 700 are in Northern Emirates.

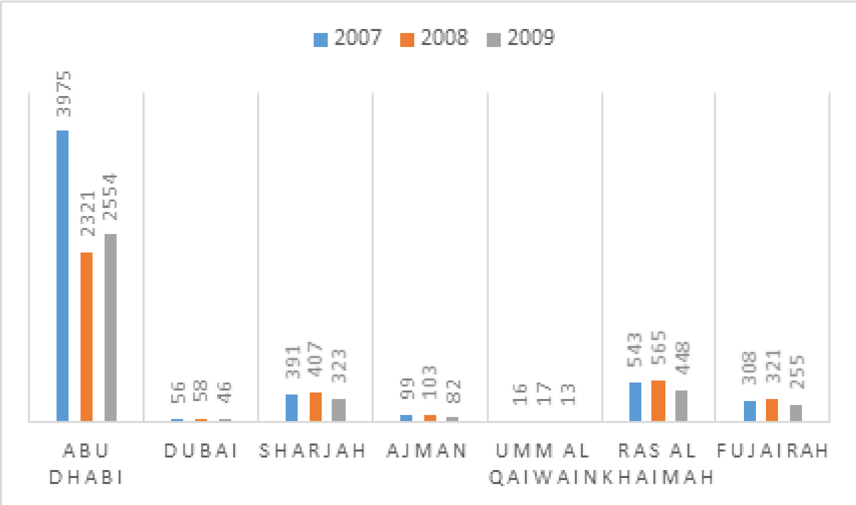

Figure 9 Total area (Dunum) of Protected Agriculture in each Emirate in the United Arab Emirates for the years 2007-2009

Source: *United Arab Emirates (the) Federal Competitiveness and Statistics Authority, 2010.*

Protected agriculture in the Abu Dhabi Emirate has received special attention because it produces high quality crops in marginal climate conditions. Despite the difficulties and challenges faced by the agricultural sector in Abu Dhabi Emirate, the sector was able to overcome most of those obstacles and attain tangible achievements by developing ambitious plans and policies to achieve long-term sustainable agricultural development. (See Table 11 and Figure 10.)

Table 11 Number and area of greenhouses in Abu Dhabi Emirate (Area in donums)

	2018	2017	2016	2015
Number	**18 269**	15 340	16 037	16 715
Area	**6 164**	5 118	5 504	5 824

Source: *Federal Competitiveness and Statistics Authority, 2010.*

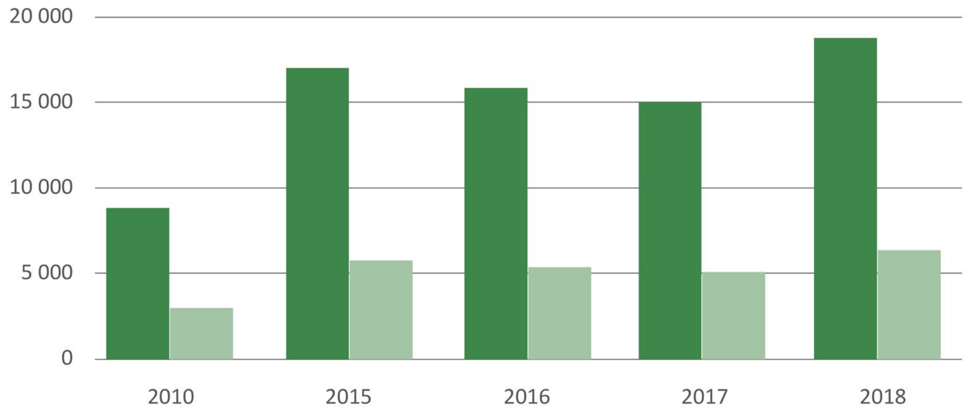

Figure 10 Number and area of greenhouses in Abu Dhabi Emirate (Area in donums)

Source: *Federal Competitiveness and Statistics Authority, 2010.*

Table 12 Number of greenhouses by region

2018	2017	2016	2015	Region
18 269	15,340	16,037	16,715	**Total**
2 070	2 130	2 227	2 105	**Abu Dhabi region**
12 056	9 394	9 821	10 390	**Al Alin region**
4 143	3 816	3 989	4 220	**Al Dhafra region**

Source: *Federal Competitiveness and Statistics Authority, 2010.*

Crops grown in Protected Agriculture

The main crops grown in the central, eastern, and northern regions, as documented by the Ministry of Climate Change and Environment (MCCE), are presented in Table 13. The productivity of the crops grown in the greenhouses is as follows: cucumber 9.8 kg/m^2, tomato 15.6 kg/m^2, pepper 11.7 kg/m^2. The average vegetable productivity in the open field was 12.1 kg/m^2.

Table 13 Typically grown crops in central, eastern, and northern regions

Region	Crops	Area planted with the crop (Dumom
Central Region		
Dhaid	Tomato, cucumber, herb, pepper, sweet peppers, eggplant, and zucchini and beans	62,700
Falaj Al Mualla	Tomato, cucumber, herb, watermelon and pepper	173,470
Kadra	Cucumber and tomato	56,500
Maliha	Cucumber and tomato	31,600
Masfoot	Tomato, cucumber, zucchini, vigna, and herb	44,750
Malki	Cucumber and tomato	10,900
Aweer	Cucumber, tomato , pepper, and okura	68,000
Ajman	Tomato, cucumber, melon, pepper, and herb	112,300
Eastern Region		
Fujairah	Cucumber, tomato, pepper, and zucchini	9,744
Kalba	Cucumber, tomato, and watermelon	2,376
Khorefkan	Cucumber, tomato, pepper	19,632
Ddnh	Cucumber, tomato	6,636
Masafi	Cucumber, tomato, pepper, and zucchini	80,802
Dibba	Cucumber, tomato, and pepper	42,268
Northern Region		
Iidhan	Cucumber , tomato	12
Shaml	-	0
Shaam	-	544
Digdaga	Pepper, tomato, cucumber, zucchini, and cabbage	179,604
Al Hamranih	Cucumber, tomato, pepper, and cantaloupe	429

Source: *Ministry of Climate Change and Environment, 2015.*

Research conducted by the MCCA showed that average water consumption for vegetable production in the open field is 520 m^3 per dunum (52 m^3 per ha), while the water consumption of crops in greenhouses with fan and pad cooling systems is 1 200 m^3 per dunum (120 m^3 per ha), of which 960 m^3 per dunum (96m^3 per ha) is used for cooling. This means that the cooling system uses four times the amount of water used for irrigation. Table 14 shows water consumption for irrigation crops grown in greenhouses and nethouses with different production systems.

Table 14 Water consumption for irrigation for crops grown in greenhouse and nethouse with different production systems

Production Type	Irrigation water consumption (Cubic meter dunom^{-1} year^{-1})
Greenhouse with fan cooling system with soil production	1 300
Greenhouses with fan cooling system with soil-less production	1 100
Nethouse without cooling system with soil production	500
Nethouse without cooling system with soilless production	200

Source: *MCCE, 2018.*

Table 15 Average water use for tomato, cucumber and capsicum in hydroponic agriculture for 10 greenhouses (total area of 2 600 square meter)

Crop	Average daily total water use (m^3 / day)	Average daily water used for cooling (m^3 / day)	Average daily irrigation requirements (m^3 /day)	Average daily reused drainage water (m^3 / day)
Tomato	38.7	28.8	9.9	3.3
Cucumber	37.0	28.8	8.2	2.7
Capsicum	37.7	28.7	8.9	3.0

Source: *Abu Dhabi Farmers' Services Centre, 2018.*

Technologies used in protected agriculture

Several types of protected agriculture structures are used in United Arab Emirates (the): single-, double- and multiple-span greenhouses, and nethouses. The single-span greenhouse (usually 8 × 34 m), with a double layer of polyethylene sheets, pad-fan cooling system and a single door, is the predominant model. In Northern Emirates, 76.2 percent of the production area is under soil production systems while 23.8 percent is under hydroponics production systems.

Economics of protected agriculture

Protected agriculture has shown a significant increase in yields over field-grown crops (such as tomatoes, at 12.5 kg/m^2 under protected cultivation, four times greater than open-field production). This is particularly the case when hydroponic systems are used. Protected agriculture usually has high capital, operational and maintenance costs, which require higher yields and higher prices in order to be profitable. Sustainability of protected agriculture is crucial and is driven by many externalities, such as shortage of water resources, marketing, and imports. Furthermore, huge amounts of water are required to cool the greenhouses, which requires more research to reduce the water used in cooling.

MCCE future support plans

Currently, the government of United Arab Emirates (the) is providing 50 percent of production subsidies as well as facilitating Khalifa fund loans for greenhouse growers. New strategies will be adopted by the MCCE on:

- providing subsidies to farmers to expand the use of protected agriculture;
- improved award distribution of Khalifa funds;
- improvements in nethouse technologies (fan and pad cooling systems, materials, design, etc.).

Main players of agricultural development

- Ministry of Climate Change and Environment (MoCCAE)
- Abu Dhabi Farmers' Service Centre (ADFSC)
- Abu Dhabi Food Control Authority (ADFCA)
- Arab Authority for Agricultural Investment and Development (AAAID)
- Environment Agency Abu Dhabi (EAD)

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ANNEX 2
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