

Good Agricultural Practices for greenhouse vegetable crops

Principles for Mediterranean climate areas



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Good Agricultural Practices for greenhouse vegetable crops

Principles for Mediterranean climate areas

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Preface

A very significant event in the world history of Agriculture is the domestication of plants by mankind. Instead of depending on wild growth, it was realized that the planting of seeds or cuttings allowed the propagation of the type of plants desired. Another important breakthrough resulted from the need to protect the domesticated plants from abiotic and biotic stress factors. Protected cultivation emerged as a way to protect crops from adverse weather conditions allowing year-round production and the application of an integrated crop production and protection management approach for better control over pests and diseases.

Greenhouse crop production is now a growing reality throughout the world with an estimated 405 000 ha of greenhouses spread over all the continents. The degree of sophistication and technology depends on local climatic conditions and the socio-economic environment.

The experience of greenhouse production, which emerged in northern Europe, stimulated development in other areas, including the Mediterranean, North America, Oceania, Asia and Africa, with various rates and degrees of success. It has been shown that a mere transposition of north European solutions to other parts of the world is not a valid process. Each environment requires further research, development, extension, training and new norms of application to meet local requirements.

During the last 20 years countries in the Mediterranean climate area have become increasingly competitive producers of greenhouse vegetables. During this time there has been a revolution in greenhouse production technology in terms of greenhouse design, type and quality of the plastic covering material, fertigation, mulch, use of high-yielding hybrids and cultivars, plant training and pruning techniques, integrated pest management, the use of pollinator insects, climate control, soil solarization etc. Only a few years ago, a yield of 100 tonnes per hectare of tomato in a greenhouse was considered a good performance. Today, for growers in Mediterranean climate areas, a harvest of 300 tonnes per hectare is not unusual.

Besides supplying the local markets, the production of greenhouse vegetables is greatly valued for its export potential and plays an important role in the foreign trade balance of several national economies in the Mediterranean region. However, the intensification of greenhouse crop production has created favourable conditions for many devastating pests and diseases. This has significantly increased the need for pesticide applications. At the same time, legislative measures and standards requirements regarding the quality and safety of vegetables have become

increasingly demanding. Consumer awareness has risen and the demand for pesticide-free products is a reality which cannot be ignored.

Since 1993, the Regional Working Group on Greenhouse Crops in the Mediterranean Region facilitated by the FAO's Plant Production and Protection Division has supported training and research and development initiatives to strengthen national capacities in upgrading the greenhouse crop sector in Mediterranean climate areas. This publication builds on experience gained through partnerships forged by the working group and represents the interpartner effort of two decades. It aims to summarize the knowledge and practical experiences of scientists from the Near East and North Africa region, specifically from Algeria, Cyprus, Egypt, Jordan, Lebanon, Libya, Malta, Morocco, the Syrian Arab Republic, Tunisia and Turkey and in collaboration with the Commission of Protected Cultivation of the International Society for Horticulture Science (ISHS) and a worldwide panel of subject matter specialists.

This technical document intends to illustrate the benefits that can be drawn from an "integrated production and protection" (IPP) approach linking production technologies and plant protection practices to minimize the use of pesticides and adopting "sustainable intensification" of greenhouse crop production as the guiding principle. It is in line with the new FAO "Save and Grow" paradigm that helps to limit agriculture's impact on climate change and strengthens resilience of open-field and greenhouse farming systems to socio-economic and climate risks.

It is believed that greenhouse crop production is destined to play an increasingly important role in the Mediterranean climate environment as a means for sustainable crop intensification leading to optimization of water-use efficiency in an environment of water scarcity in addition to better control of product quality and safety, in line with the market demand, standards and regulations.

By sharing their knowledge and experience, the authors of this publication wish to sustain the competitiveness of the vegetable greenhouse sector in the Mediterranean climate areas and contribute to its further development to the benefit of growers, consumers and the environment.

This publication discusses the principles of Good Agricultural Practices (GAP) as they may be applied to greenhouse farming in the Mediterranean climate areas. It illustrates different aspects of greenhouse crop production and protection with special emphasis on greenhouse technologies, design and climate control, cropping systems, in particular those practices which help reduce pests and diseases incidence in crops, integrated pest management, the use of adapted cultivars, and the need for traceability and product labelling.

The guidebook is expected to serve as a training guide for trainers and a resource document for advanced growers and stakeholders of the greenhouse vegetable value chain. It is also a valuable source of information for programme managers, international and multilateral development organizations, NGOs and the private sector – as well as researchers, advisors and professionals in greenhouse agriculture. We trust that it will help to further strengthen the work of the FAO-facilitated Regional Working Group on Greenhouse crops in the Mediterranean Region.

Abdessalam Ould Ahmed

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Office of the Near East

List of acronyms and abbreviations

AAP	Air acidification potential
ADI	Acceptable daily intake
ADP	Abiotic depletion potential
AESA	AgroEcoSystem Analysis
AFP	Air-filled pore space
AGN	FAO Food Safety and Quality Division
AGP	FAO Plant Production and Protection Division
ALARI	Arid Land Agricultural Studies and Research Institute
AoP	Areas of protection
ARI	Agricultural Research Institute
ASABE	American Society of Agricultural and Biological Engineers
ASEAN	Association of Southeast Asian Nations
ATP	Adenosine triphosphate
BER	Blossom end rot
BSI	British Standards Institution
CA	Controlled atmosphere
CB	Certification body
CEC	Cation exchange capacity
CED	Cumulative energy demand
CEN	European Committee for Standardization
CFD	Computational fluid dynamics
CGMMV	Cucumber green mottle mosaic virus
CHP	Combined heat and power
CI	Chilling injury
CMV	Cucumber mosaic virus
CNL	Compensated no leakage
CPCC	Control Points and Compliance Criteria
CVYV	Cucumber vein yellowing virus
CWSI	Crop Water Stress Index
CYSDV	Cucurbit yellow stunting disorder virus

DE	Delivery efficiency
DFT	Deep flow technique
DIF	Day-night temperature difference
DT	Day temperature
DTPA	Diethylene triamine pentaacetic acid
DU	Distribution uniformity
DWC	Deep water culture
EAW	Easily available water
EBA	Ethylene butyl acrylate
EBI	Ergosterol biosynthesis inhibitor
EC	Electrical conductivity
EDDHA	Ethylene diamine di-o-hydroxyphenylacetic acid
EDTA	Ethylene diamine tetraacetic acid
EPC	Electronic product code identification
EPS	Effective pore space
ET	Economic threshold
ETc	Crop evapotranspiration
ETo	Reference evapotranspiration
EUP	Eutrophication potential
EVA	Ethylene vinyl acetate
EW	Equivalent weight
FDR	Frequency domain reflectometer
FE	Farm efficiency
FFS	Farmer field school
FH	Float hydroponics
FU	Functional unit
FW	Fresh weight
FYM	Farmyard manure
GAP	Good agricultural practice
GFT	Gravel film technique
GGN	GLOBALG.A.P number
Gm	Granular matrix
GMO	Genetically modified organism
GMP	Good manufacturing practice

GRIS	Greenhouse Information System
GWP	Global warming potential
HACCP	Hazard analysis and critical control point
HAF	Horizontal airflow
HEDTA	Hydroxyethyl ethylene diamine triacetic acid
IAA	Indoleacetic acid
ICS	Inductively coupled plasma
IE	Irrigation efficiency
IFA	Integrated farm assurance
IGR	Insect growth regulator
IOBC	International Organization for Biological Control of Noxious Animals and Plants
IPM	Integrated pest management
IPPM	Integrated production and pest management
IR	Infrared
IRTA	Institute for Food and Agricultural Research and Technology
IS	Irrigation scheduling
ISHS	International Society for Horticultural Science
K _c	Crop coefficient
K _p	Pan coefficient
LAI	Leaf area index
LCA	Life cycle assessment
LCI	Life cycle inventory
LDPE	Low density polyethylene
LER	Land equivalency ratio
LLDP	Linear low density polyethylene
LP	Local practice
MA	Modified atmosphere
MBr	Methylbromide
MOA	Ministry of Agriculture (Jordan)
MRL	Maximum residue level
NCARE	National Center for Agricultural Research and Extension
NFT	Nutrient film technique
NIR	Near infrared

NPV	Nuclear polyhedrosis virus
NT	Night temperature
NUE	Nitrogen-use efficiency
PAR	Photosynthetically active radiation
PDCA	Plan-Do-Check-Act
PDSA	Plan-Do-Study-Act
PE	Polyethylene
PepMV	Pepino mosaic virus
PGR	Plant growth regulator
PHU	Produce handling unit
PMMA	Polymethyl methacrylate
PMU	Production management units
PVY	Potato virus Y
QMS	Quality management system
QR	Quick response
RDWC	Recirculating deep water culture (system)
REI	Re-entry interval
RFID	Radio frequency identification
RH	Relative humidity
RIS	Relative irrigation supply
RNA	Ribonucleic acid
SAR	Sodium adsorption ratio
SAS	Safety access system
SCIS	Soilless Culture Information System
SNFT	Super nutrient film technique
SOM	Soil organic matter
SOP	Standard operation practice
STV	Salinity threshold value
SYD	Salinity yield decrease
TCP	Technical Cooperation Programme
TDR	Time domain reflectometer
TDR	Time domain refractometry
TDS	Total dissolved solids
TDT	Time domain transmissiometry

TI	Temperature integration
TMV	Tobacco mosaic virus
TPS	Total pore space
TSWV	Tomato spotted wilt virus
TYLCV	Tomato yellow leaf curl virus
UNDP	United Nations Development Programme
UNEP	United Nations Environment Programme
UV	Ultraviolet
VPD	Vapour pressure deficit
YSD	Yellow shoulder disorder
WBC	Water buffer capacity
WE	Watering efficiency
WFT	Western flower thrip
WFS	Wood fibre substrate
WP	Water productivity
WPRS	West Palaeartic Regional Section (IOBC)
WUE	Water-use efficiency
ZYMV	Zucchini yellow mosaic virus

1. Regional Working Group on Greenhouse Crop Production in the Mediterranean Region: History and development

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FAO'S PLANT PRODUCTION AND PROTECTION DIVISION (AGP): APPROACH AND ROLE IN PROMOTING REGIONAL COOPERATION IN SUPPORT OF GREENHOUSE CROP PROTECTION

In line with the “Save and Grow” concept, AGP works to strengthen global food security by promoting sustainable crop production intensification, which aims at producing more from the same area of land while conserving resources, reducing negative impacts on the environment and enhancing natural capital and the flow of ecosystem services.

AGP's mandate is to enhance and strengthen:

- effective and strategic decisions that increase crop production using an ecosystem approach and nutrition-sensitive crop diversification;
- national capacities to monitor and respond effectively to transboundary and other important outbreaks of pests;
- policies and technologies appropriate to needs of member countries to reduce the negative impact of pesticides; and
- conservation and sustainable use of plant genetic resources with strong linkages between conservation, plant breeding and seed sector development.

As part of its programme areas, AGP supports the development of greenhouse technology for horticulture and high-value crops as a means for sustainable crop intensification. To this effect, a Regional Working Group was created 20 years ago, in 1993, to enhance south-south cooperation among the national institutions

and scientists from Near East and North Africa (NENA) countries¹ and to facilitate interactions with cooperating scientists and institutions from northern countries, such as Belgium, France, Germany, Greece, Italy and Spain.² Together, they formed a network to enhance intercountry cooperation for the improvement of greenhouse crop production technology in the Mediterranean region. In these countries, protected cultivation is continuously expanding leading to improved water-use efficiency, increased productivity per unit input and land, improved product quality, reduced use of pesticides as a result of integrated pest and disease control. Simple tunnel-type greenhouses and more sophisticated structures are evolving side by side depending on the cost-effectiveness. Plastic film is the predominant covering material in Mediterranean climate areas. Out of an estimated 220 000 ha of greenhouses in the Mediterranean countries, 90 percent are covered with plastic and 10 percent with glass.³

The Working Group has been focusing its activities in three main areas:

- Information management and dissemination
- Training and demonstration
- Project formulation and implementation

SCOPE OF THIS PUBLICATION AND MAIN OBJECTIVES

The publication of *Good agricultural practices for greenhouse vegetable crops: Principles for Mediterranean climate areas* is a major achievement and also a key milestone of the FAO Regional Working Group on Greenhouse Production in the Mediterranean Region. Its scope is to capitalize the know-how and experiences of the FAO network of scientists which since the creation of the Regional Working Group have studied and debated a wide range of crop- and technology-related aspects of greenhouse crop production and protection.

The main objectives of this publication are:

- Provide a compilation of greenhouse production practices and technologies presently in use in Mediterranean climate areas that have helped increase vegetable production, productivity and quality.
- Provide recommendations on good agriculture practices based on the current best knowledge of the different crop and technology aspects for greenhouse vegetable cultivation in Mediterranean climate areas.

¹ Algeria, Cyprus, Egypt, Jordan, Lebanon, Libya, Malta, Morocco, the Palestinian Authority, the Syrian Arab Republic, Tunisia and Turkey.

² Please refer to p. 9 for the comprehensive list of cooperating scientists and institutions.

³ Tuzel, Y. and Leonardi, C. 2010. Protected cultivation in Mediterranean region: trends and needs. *Journal of Ege University Faculty of Agriculture*, 46(3): 215–223.

The document is in line with the new FAO “Save and Grow” paradigm that advocates the sustainable intensification of farming systems and strengthens their resilience to socio-economic and climate risks. The publication is meant to be a reference document for scientists, teachers and students, as well as private sector entrepreneurs. It is proposed as a training support document for upgrading the technical know-how of trainers and pilot growers as well as other actors in the greenhouse vegetables value chain in Mediterranean climate areas.

ORIGIN AND OPERATIONAL MODALITIES OF THE GREENHOUSE REGIONAL WORKING GROUP

The premises leading to the establishment of the FAO Working Group in the Mediterranean Region date back to February 1984. On the occasion of the ISHS Symposium on “Plastics for Horticulture in the Mediterranean Region” in Hammamet, Tunisia, the decision was made to prepare a position paper on the greenhouse production technology in the Mediterranean region based on the contributions of selected collaborators.

In September 1984, following a meeting with the Faculty of Horticulture at the State University of Gembloux, Belgium, an agreement was reached on the content and authors of a position paper entitled “Intensification of Horticulture Crop Production under Protected Cultivation in the Mediterranean Region”. In June 1985 the members of the drafting committee met in Gembloux to review the first draft under the joint supervision of Professor André Nisen, Faculty of Horticulture, Gembloux and Professor Giuseppe Lamalfa, University of Catania, Italy. The advanced draft was discussed in December 1985 during the ISHS workshop on “Protected Cultivation of Solanaceae Crops” in Faro, Portugal. The document was finally published in 1988 as the FAO AGP Technical Paper No. 90, initially in English and subsequently translated into French, Spanish and Arabic.

The actual establishment of the FAO Working Group on Greenhouse Crop Production in the Mediterranean Region, referred to as the WG, emerged from the recommendation formulated by the participants at the Expert Consultation Meeting on Protected Cultivation convened by Dr Abderahmane Hilali, Director of the Complexe Horticole (Institut Hassan II) in Agadir, Morocco in November 1993. The WG group is composed of scientists and decision-makers representing 12 countries from the Near East and North Africa region, namely Algeria, Cyprus, Egypt, Jordan, Lebanon, Libya, Malta, Morocco, the Palestinian Authority, the Syrian Arab Republic, Tunisia and Turkey.

As a result of a consultation process, the group members agreed on the scope, objectives and operational modalities for the WG. Realizing the complexity and the interaction of different disciplines for successful greenhouse crop management, they recommended that the scope of the WG should be to promote an “integrated approach” for sustainable greenhouse crop production intensification aiming at

improved product quality and safety with a view to reducing the use of pesticides and applying alternative methods for pest and disease control. The concept of integrated production and protection (IPP) was officially introduced by the WG – as a precursor of the GAP concept – on occasion of the International Symposium on Integrated Production and Protection of Horticultural Crops, convened by Dr Abdelhaq Hanafi (then Professor at Complexe Horticole of IAV Hassan) in Agadir, Morocco, in May 1997.

The WG members adopted the following three types of interrelated activities for the programme of the WG:

- Assessment of greenhouse production technologies for transfer to growers
- Strengthening of capacity building
- Implementation of joint research and development initiatives

The disciplines to be covered were grouped in four thematic areas (TA), each animated by a technical coordinator (TC).

Disciplines covered

- **TA1:** Irrigation, fertigation, soilless culture (**TC:** Ayman Abou Hadid, Egypt)
- **TA2:** Greenhouse design, covering materials, climate control, including geothermal water use (**TC:** Abdelaziz Mougou, Tunisia)
- **TA3:** IPP: Integrated production and protection management (**TC:** Abdelhaq Hanafi, Saudi Arabia)
- **TA4:** Production economics, quality requirements, crop diversification, organic horticulture (**TC:** Yuksel Tuzel, Turkey)

The activities in the four thematic areas were grouped into three categories:

- Information exchange
- Training and field demonstrations
- Project formulation and implementation

From an operational point of view, the WG activities are facilitated by a WG coordinator, belonging to one of the participating countries and with an office term of 2 years. The WG programme is discussed at the WG coordinating meeting held every 2 years to review the progress and achievements in the past biennium, agree on a work plan for the coming biennium and elect the WG coordinator. Most of the activities are implemented by countries drawing on their own resources or with project support. The coordinating meeting is hosted by the country of the “incoming” regional coordinator elected at the previous coordinating meeting.

ACTIVITIES, RESULTS AND ACHIEVEMENTS OF THE WORKING GROUP

Capacity building has been pursued through a series of FAO-sponsored technical workshops. As a group, the network members play a leading role in promoting the exchange of information on greenhouse crop technology and have been able to organize several international symposia, often in conjunction with the Commission Protected Cultivation of the International Society for Horticulture Science:

- Integrated production and protection (IPP) of horticulture crops, Agadir Morocco, 6–9 May 1997
- Strategies towards sustainability of protected cultivation in mild winter climate, Antalya, Turkey, 3–5 Nov. 1997
- Growing media and hydroponics, Thessaloniki, Greece, 4–5 Sept. 1999
- Greenhouse floriculture, production and export of cutflowers, Tunis, Tunisia, 9–10 June 2000
- Greenhouse vegetable production standards for quality and safety, Beirut, Lebanon, 6–7 May 2001
- Vegetable breeding and seed production, Cairo, Egypt, 12–16 Dec. 2001
- Organic greenhouse vegetable production, Amman, Jordan, 28–29 Jan. 2002
- Protected cultivation in mild winter climate: product and process innovation, Ragusa, Italy, 5–8 Mar. 2002
- Flowers for the future, Izmir, Turkey, 7–11 Oct. 2002
- Integrated greenhouse production and protection (IGPP), Beirut, Lebanon, 8–9 Mar. 2003
- Soilless culture technologies, Izmir, Turkey, 5–6 Mar. 2004
- Greenhouse cooling, Almería, Spain, 23–24 May 2006
- Sustainable greenhouse crop production technologies in mild winter climates, Antalya, Turkey, 6–11 April 2008

Exchange of information has been facilitated through the publication of technical documents and proceedings of workshops and symposia, which have been posted on the WG Web site <http://www.NenaGreenhousesFao.org>. The WG has produced the following documents:

- Country surveys and technical recommendations for the greenhouse crop sector in Cyprus, Egypt and the Syrian Arab Republic
- Technical guidelines on irrigation management
- Practical guidelines for cut-flower production in Tunisia

Some 3 200 datasets on the performance of horticulture cultivars in greenhouse cultivation have been inserted in Hortivar⁴ as well as 39 “Good Morning Horticulture” messages. The countries have submitted 64 pairs of “IPP cards”, illustrating GAPs for greenhouse crops, which have been uploaded in Hortivar.

Templates have been designed and statistical information compiled on soilless culture systems in the Mediterranean countries in the Soilless Culture Information System (SCIS). Templates and statistical information on the greenhouse crop sector in Mediterranean countries has also been compiled in the Greenhouse Information System (GRIS). Both SCIS and GRIS have been integrated into Hortivar. Research for development has been strengthened and transfer of know-how to growers has been facilitated through the formulation and implementation of field projects.

The WG, with the assistance of FAO, has been able to formulate research-development projects and has obtained funding from EU, UNDP and TCP.

The FAO regional project, **TCP/INT/0165** established demonstration and training greenhouses in each of the participating countries. The objective of the project was to prepare growers to join GAP schemes like GLOBALG.A.P. by demonstrating and providing training for the adoption of integrated production and protection management (IPP) in greenhouse crops, aiming at healthy and high quality produce, sustainable productivity and reduced use of pesticides.

EU-funded **ECOPONICS** project, “Efficient water use through environmentally sound hydroponic production of high quality vegetables for domestic and export markets in Mediterranean countries” (2002–06). The project investigated simplified, economical and water-use-efficient hydroponics systems. Under the scientific coordination of the Technical University of Munich, it demonstrated the economic feasibility of ECOPONICS technology for vegetable enterprise development in Jordan, Turkey, Egypt and Morocco. It produced a set of tools – “standard operation practices” (SOPs) – for farmers, technicians and extension specialists, highlighting the advantages in relation to water management, salinity and product quality compared with traditional cultivation practices for export and domestic markets

TCP/TUN/8823. The project succeeded in demonstrating the potential of flower diversification options in order to capture export market niches and to supply the local market demand. Cost-benefit studies have been carried out to establish the comparative advantage of specific flower crops and farmers have been trained in applying improved and intensified cultivation practices.

⁴ Hortivar: FAO’s database on the performances of horticulture cultivars and platform for access to and sharing of information on the horticulture sector in general.

TCP/LEB/0067 (phase I) followed by TCP/LEB/2906 (phase II) “Rehabilitation of greenhouse vegetable production standards for safety and quality”. The overall objective is to restore small-scale farmers’ capability to produce high quality and safe vegetables under protected cultivation. The immediate objective of the project was to demonstrate “in field” cropping seasons by *in situ* demonstrations of improved production technologies and cultivation practices aimed at increasing vegetable yields and product safety and quality, lowering production costs, adopting more efficient greenhouse design and avoiding the disadvantages of the traditional greenhouse.

UNDP/EGY/95/002 “Protected cultivation”. The objectives of the agriculture strategy in Egypt are to increase agricultural productivity per unit of land and water through more efficient use of limited resources, reduction in the cost of production and thereby increase in the national output and farmers’ incomes. To fulfil these objectives, the project was designed to support the development and adoption of new technologies. Protected cultivation and soilless culture were recognized as efficient and promising technologies for attaining the set objectives.

CAPITALIZATION

On occasion of the Sixth WG Coordinating Meeting, held in Amman, Jordan in December 2006, the participants considered that the time was appropriate to take stock of the information accumulated and the experiences gained since the publication of the FAO AGP Technical Paper No. 90. They recommended that FAO take the lead in compiling a multi-author technical document which would serve the double purpose of compiling the know-how gained and making it available to growers and stakeholders in the greenhouse crop sector in the NENA region with a view to sustaining its competitiveness.

The overall guidelines and the identification of potential authors for the drafting of a publication on “Good Agricultural Practices (GAP) for greenhouse vegetable crops: Principles for Mediterranean climate areas” were elaborated on occasion of an FAO-ISHS workshop, which took place in June 2009 at the International Symposium on High Technology for Greenhouse Systems, Greensys 2009, hosted by the University of Laval, Quebec, Canada. Subsequently, an expert meeting was convened in Amman, Jordan in May 2010, which brought together the lead authors and allowed to discuss further the scope and target audience of the publication and to elaborate the table of contents. The members of the drafting committee met in Lisbon in August 2010 on occasion of the International Horticulture Congress to discuss and review the progress on the drafting of the document followed by a second business meeting in June 2011 on occasion of the Greensys Symposium in Halkidiki, Greece.

Editing took place during 2012. The final draft version was shared with the authors and participants at the International Workshop on “Good Agriculture

Practices – GAP – for greenhouse crops in the Mediterranean region”, jointly convened by ISHS, NCARE and FAO from 9 to 12 December 2012 in Jordan. Early 2013 allowed for a final peer review, proofreading and printing.

THE WAY FORWARD

The activities of the FAO Regional Working Group on Greenhouse Crop Production in the Mediterranean Region has undoubtedly impacted on the improvement of the greenhouse production sector in the NENA countries and has contributed to its mutation from a somewhat empiric activity into a professional enterprise with scientific bases.

The WG members are committed to continuing their cooperation and determined to seek opportunities to jointly implement research and development projects of common interest in support of the greenhouse crop sector in the Mediterranean climate areas. As a network of scientists, they will pursue their interaction with FAO and serve as a resource for information exchange, training and capitalization of know-how.

RECOMMENDED READING

Proceedings and technical country reports of the Working Group coordinating meetings held in:

- Agadir, Morocco, Nov. 1993
- Cairo, Egypt, 15–16 Dec. 1995
- Izmir, Turkey, 6–7 Nov. 1997
- Catania, Italy, 16–18 Dec. 1999
- Beirut, Lebanon, 4–6 Feb. 2002
- Nicosia, Cyprus, 13–14 Nov. 2003
- Amman, Jordan, 19–20 Dec. 2006

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2. Greenhouse site selection

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INTRODUCTION

In recent decades, greenhouse area has risen worldwide, due mainly to the increased use of plastic greenhouses for growing vegetable crops. Site selection is a key factor for profitable and sustainable greenhouse production. The main factors determining location and site selection of a greenhouse production area are: cost of production, quality of produced yield, and transportation cost to markets (Nelson, 1985; Castilla, 2007). Obviously, cost and quality of production depend on the local climate and the greenhouse growing conditions. The level of investment in technology (simple or sophisticated greenhouses and equipment), as well as management, depends primarily on the local climate.

Nowadays, long distance transportation means that production areas may be located far from major consumption centres, enabling the development of greenhouse industries in many climatically favourable areas around the world, such as the coastal zones of the Mediterranean Basin (Plate 1). In addition to transportation, marketing (standardization, packing etc.) also affects the overall cost of the products; they tend to be similar for different commodities coming from different geographical origins, but which compete in the same markets (Castilla *et al.*, 2004).

This chapter examines the climatic conditions required for the production of greenhouse crops, in particular vegetables.

GREENHOUSE MICROCLIMATE MODIFICATION

From a historical point of view, the initial objective of greenhouse cultivation was to grow heat-demanding species during the winter season in temperate countries, i.e. countries with a cold winter season. Inside greenhouses more favourable temperatures may be reached during the cold season, thanks to the windbreak effect and the



Plate 1
Poniente area (Almería, Spain)



Plate 2

Banana crop in a greenhouse

greenhouse effect. During the warm season, especially in the Mediterranean and tropical areas, where there is high solar radiation and the temperature exceeds the recommended maximum threshold level, the greenhouse effect has an adverse impact on the microclimate and crop performance. However, these negative effects are to some extent compensated for by the shading effect and can be regulated to a certain extent by proper ventilation and/or cooling of the greenhouse.

The greenhouse effect is the result of two different effects:

- a confinement effect, resulting from the decrease in the air exchanges with the outside environment; and
- an effect caused by the existence of a cover characterized by its low transparency to far infrared radiation (emitted by the crop, the soil and the inner greenhouse elements), but its high transparency to sunlight.

The use of cladding greenhouses with screens (nets) throughout the year, instead of plastic films, has become common practice in recent years in areas of very mild temperature (low latitudes) and in areas where temperatures are very mild in selected periods (medium latitudes in spring and summer). In these “screenhouses”, the greenhouse effect is minimal, as the confinement effect is very limited and sunlight is reduced (as screens’ transparency to sunlight is, normally, lower than in conventional greenhouse plastic cladding films). This minimal greenhouse effect varies according to the characteristics of the screens (permeability for air exchanges with the outside environment and transparency to sunlight), while the shading and windbreak effects prevail. Screenhouses do not protect crops from rainfall, as their cover is permeable, but they can reduce the damage caused by heavy rain and hail.



Plate 3

Year-round supply of high-quality products

GREENHOUSE PRODUCTION STRATEGIES

When planning the installation of a greenhouse, two main questions must be answered (Jensen and Malter, 1995):

- Where will the production be marketed (domestic or export markets or both)?
- What type of commodities will be produced (edible or ornamentals)?

In general, optimum climatic conditions and low production costs (with good quality) are key to the selection of a location; transportation costs are also an important consideration when markets are far away (Castilla, 2007). Other technical and socio-economic aspects (water and electricity supply, labour availability etc.) also influence production costs and competitiveness (Castilla and Hernandez, 2005).

There is currently a high demand from consumers for a year-round supply of quality products (Plate 3), conditioning the production strategies in the greenhouse industry. Greenhouse crops in mild winter climates, such as in the Mediterranean area, cannot be grown all year round with high quality. The challenge of supplying high quality vegetables all year round can be met by adopting one of two basic strategies:

- Growing in high-tech greenhouses, avoiding strong dependence on the outdoor climate.
- Growing in two or more locations with complementary harvesting periods, enabling a continuous and coordinated year-round supply to markets (Castilla and Hernandez, 2007).

The second alternative (using different locations, usually with different greenhouse technological levels) is an increasingly adopted strategy.

In some regions, including the Mediterranean, adapting plants to a suboptimal environment has in the past been the most common production strategy. In contrast, in northern Europe, the favoured approach has been to optimize the greenhouse environment in order to reach maximum potential yields. Nowadays, market globalization has led to greater competitiveness; it is therefore necessary to increase the quality of greenhouse products through better climate control (Castilla and Montero, 2008).

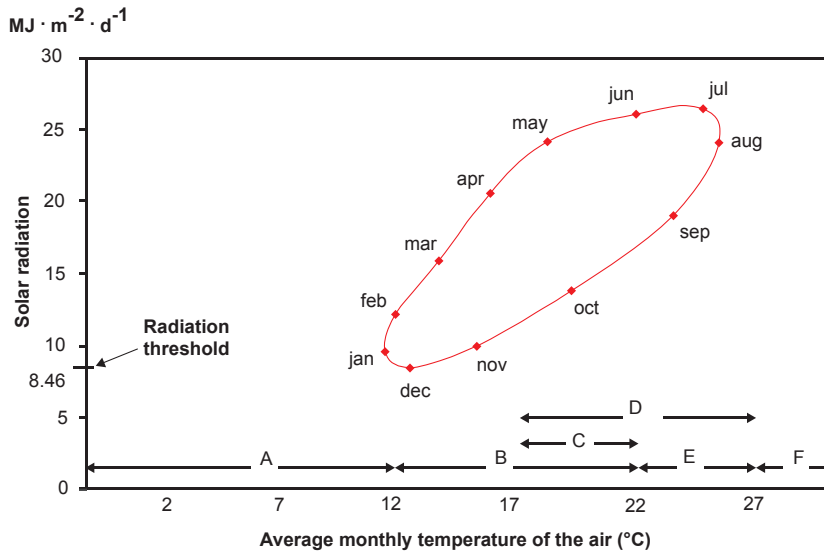
CLIMATIC SUITABILITY FOR GREENHOUSE VEGETABLE PRODUCTION

Introduction

Today's greenhouse technologies mean it is possible to cultivate all horticultural species in any region of the world, provided that the greenhouse is properly designed and equipped to control the climatic parameters. However, for profitable and sustainable cultivation of the target crop, much stricter selection of the region is necessary, on the basis of climatic conditions and the requirements of the selected horticultural crop.

Solar radiation is the main climate parameter needed to evaluate the climate suitability of a region for protected cultivation. Day length and solar radiation intercepted by a horizontal surface during daytime hours are measured to determine total daily solar radiation. Another basic climate parameter is ambient temperature. The stability of both values in different months of the year enables

FIGURE 1
 Estimation of climate suitability of Almería (Spain, 37°N) for cultivation of thermophilic vegetable species in greenhouses, from the monthly average values of ambient temperature and solar radiation



A Heating required
 B Protected cultivation possible without climate control but with natural ventilation (passive)
 C Open air cultivation possible (inland areas)

D Open air cultivation possible (coastal areas)
 E Need to use techniques to decrease temperatures
 F Excessive temperatures

Nisen *et al.*, 1988 (adapted)

the representation of their mean monthly values (obtained by averaging data sets for several years) for a given location in the climate diagram, which represents the location's climate (Figure 1).

Other climate parameters, such as soil temperature (closely linked to air temperature), wind, rainfall and air composition (humidity and CO₂), influence to a lesser degree the evaluation of climate suitability.

The type of greenhouse adopted depends on the region's climatic characteristics and on the crop requirements. For example, in a region with a tropical humid climate, where protection from rain is the greenhouse's main purpose (prevalence of the umbrella effect), the type of construction preferred may be different from that desirable in a semi-desert or Mediterranean climate region (Plate 4).

Climatic requirements of vegetables

The most commonly grown species in greenhouses are vegetables with medium thermal requirements (tomato, pepper, cucumber, melon, watermelon, marrow,

green bean, eggplant); the aim is to extend the growing calendars beyond the conventional open-air cultivation season, and thus increase profitability (Plate 5). Nowadays, the production of greenhouse crops in geographical areas without suitable climate conditions, is highly questionable since it entails significant and expensive artificial climate control. In any case, economic results determine the final selection of a greenhouse project location.

The indicated species, traditionally grown in the warm season, are adapted to average ambient temperatures ranging from 17 to 28 °C, with limits of 12 °C (minimum) and 32 °C (maximum) (Nisen *et al.*, 1988). They are sensitive to the cold and suffer irreversible damage with frosts.

Temperatures persistently below 10–12 °C over several days affect productivity, as do temperatures above 30 °C (in the case of dry air) or 30–35 °C (in the case of high air humidity) (Nisen *et al.*, 1988). Daily variation between day and night average temperatures (thermal periodicity) is required for proper physiological functioning. These thermal differences are between 5 and 7 °C (Nisen *et al.*, 1988).

The minimum daily radiation requirements of these species are estimated at around 8.5 MJ m⁻² day⁻¹ (equivalent to 2.34 kWh m⁻² day⁻¹) during the three shortest months of year (November, December and January in the Northern Hemisphere; May, June and July in the Southern Hemisphere). This means around 6 hours of light per day, to a minimum total of 500–550 hours of light during these three months (Nisen *et al.*, 1988). The duration of the day and night and, consequently, the total solar radiation depend on the geographical latitude and the time of the year (Table 1).

Other desirable climate parameters for these species would be soil temperature of > 14 °C and ambient relative humidity of 70–90% (Nisen *et al.*, 1988).



Plate 4

Protection against rain in regions of high rainfall



Plate 5

Tomato: widespread in Mediterranean greenhouses

TABLE 1
Values of maximum global solar radiation intensity (W/m²) predictable as a function of latitude (midday, Northern Hemisphere)

Latitude	Dec.	Mar.	June	Sept.
32°N	550	915	1 050	855
38°N	455	845	1 025	780
44°N	355	770	995	685

Nisen *et al.*, 1988

Obtaining the required climate conditions

The difficulty of increasing, at a reasonable cost, the natural radiation conditions (except in very sophisticated greenhouses and with high-value crops) makes it necessary to design and locate greenhouses to optimize the interception of solar radiation during the autumn and winter months. Therefore, the natural radiation conditions are the main limiting factor to consider when establishing greenhouses.

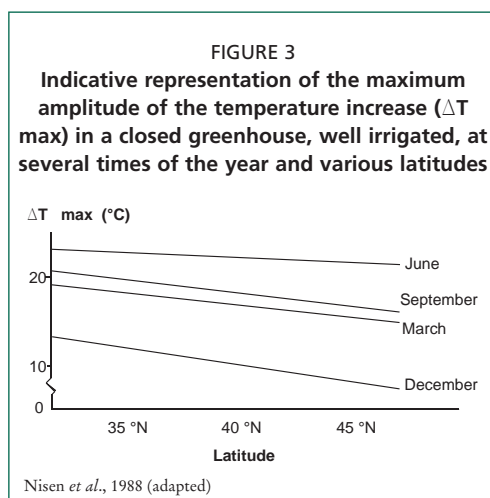
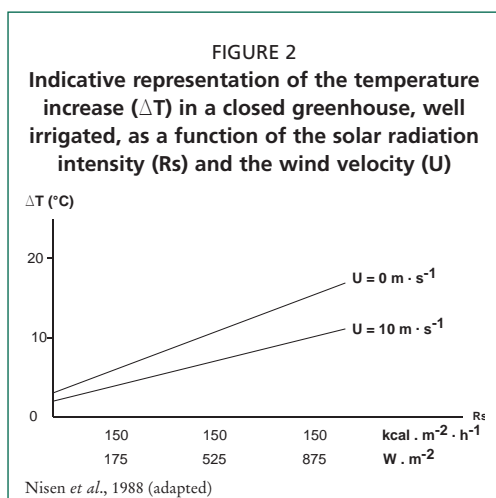
Given the parallelism between air and soil temperatures (even with less oscillation inside a greenhouse than in the open air), achieving a suitable ambient temperature also involves proper soil temperature values. FAO proposed a methodology for achieving the required climate conditions (Nisen *et al.*, 1988).

Protected cultivation in greenhouses or high tunnels causes the increase of daytime temperature (in relation to the outside) to very high values (Figure 2), depending on:

- characteristics of the cladding material;
- outside wind velocity;
- incident solar radiation;
- transpiration of the crop grown inside the greenhouse.

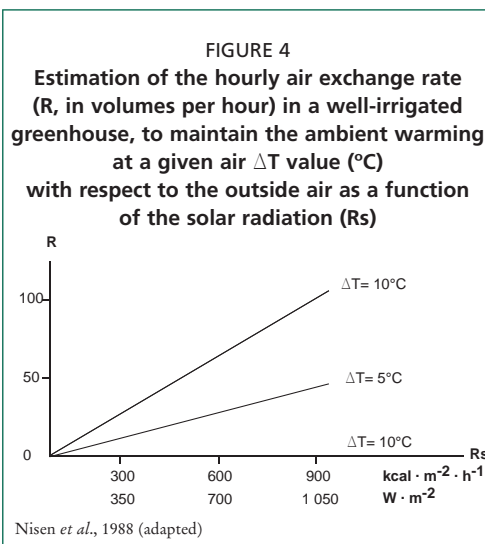
Night temperatures, on the other hand, only increase slightly in relation to the outside (2–4 °C at the most) and, in some cases, are lower (thermal inversion). The maximum temperature increase varies with latitude and, for each specific location, with the time of year as the solar radiation changes (Figure 3).

To increase low temperatures, the most common solution is to heat the greenhouse, but this is not always profitable. In some cases, an efficient isolation system can prevent temperature drop at night – as in the “lean-to greenhouse” in



China, where a curtain of canes and wood is manually placed over the greenhouse cover at sunset, then removed at sunrise. This solution prevents major temperature decreases at night, but is highly labour-intensive. To limit temperature excesses, the renewal of interior air by means of ventilation is the classic and most economic tool.

The hourly air renewal rate needed to keep the temperature gradient at a certain value, depending on maximum predictable solar radiation, can be very high (Figure 4) and impossible to achieve without mechanical ventilation.



Climate suitability

The fundamental requirements of those thermophilic horticultural species for which there is a high demand for out-of-season cultivation (tomato, pepper, melon, watermelon etc.) are as follows (Nisen *et al.*, 1988):

- Minimum global radiation of 8.5 MJ/m²/day (equivalent of 2.34 kWh/m²/day).
- Average ambient temperatures of 17–27 °C in coastal areas and 17–22 °C in inland areas (far from the sea). This distinction is based on the fact that the daily thermal oscillations of inland areas (around 20 °C) are higher than those of coastal areas (10 °C)

It is not economically viable to actively control the microclimate in unsophisticated greenhouses, and minimum greenhouse temperatures are therefore very similar to those in the open air, especially when there are no heating systems. The maximum temperatures with passive normal ventilation can be around 10 °C higher than outside, involving an increase in the average temperatures of about 5 °C. In the light of these considerations, the thermal climate limits for protected cultivation without active climate control equipment are 12–22 °C in coastal areas and 12–17 °C in inland areas. Outside these limits, protected cultivation requires active climate controlling systems: heating, mechanical ventilation and cooling.

Figure 1 represents the climate diagram of Almería. Solar radiation in December is at its minimum. Temperatures are slightly below 12 °C (minimum threshold) in January, and heating is therefore necessary. With the exception of the summer (June, July, August and September), the remaining months present thermal conditions suitable for protected cultivation (12–22 °C) with efficient ventilation. In the summer, thermal excesses must be limited to cultivate inside greenhouses.

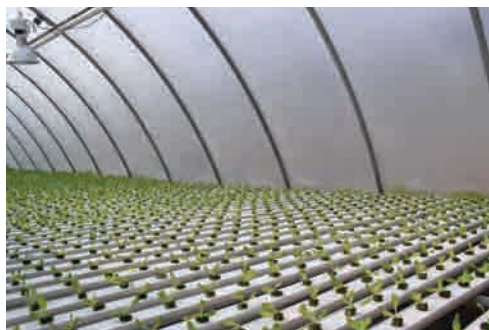


Plate 6

Lettuce greenhouse cultivation: species with lower thermal requirements prevail when cold

Obviously, the indicated method constitutes only a primary approach to evaluating the climate suitability of a region for the cultivation of thermophilic vegetable species. Similarly, it is possible to evaluate the climate suitability of a certain location for greenhouse cultivation of other less thermal-demanding species, such as lettuce and Chinese cabbage (Plate 6).

The use of screens instead of plastic films as covering material induces a minimal greenhouse effect, generating shading and windbreak effects. Screenhouses are an option for protected cultivation and are becoming more widespread in low-rainfall areas with very mild winter temperatures, and in highlands at medium latitudes during the summer.

GREENHOUSE LOCAL SITE

The specific selection of a greenhouse location must take into account a variety of factors (Castilla, 2007), described below.

Topography

In principle, the location must be flat in width direction, with a slope in the main axes between 0 and 0.5 percent, and never over 1–2 percent, as this would require terracing. In some cases, however, a south-oriented inclined plot (in the Northern Hemisphere) may be acceptable if the chosen greenhouse type adapts well; in this case, mechanization is rare (such as on Spain's south coast, where low-cost greenhouses are common on the coastal slopes – Plate 7). Normally, on steep terrains, it is recommended to build several separate greenhouses with axes parallel to contour lines. Provisions must be made for the evacuation of rainfall water, and greenhouses should not be situated in hollow lands.



Plate 7

Coast of Granada (southern Spain): south-facing slopes with better solar radiation in autumn and winter

Microclimate

As with liquids, cold air moves downwards (as it is heavier than hot air) to the lower parts of the site, and stays there if there is no wind to carry it away. Therefore, it is essential that the local topography is suitable for effective drainage of cold air during calm nights. Frequently foggy areas should be avoided. Areas that are well illuminated and free from shadows (hills, buildings) are preferred.

Harsh weather conditions

Sites should be protected from cold winds (usually from the north in the Northern Hemisphere), using windbreaks or taking advantage of the topography. If snow is to be expected, greenhouses must be positioned sufficiently far from trees or other obstacles to the wind, since snow may accumulate around such obstacles.

Irrigation

It should be emphasized that the availability of water (in sufficient quantity and of good quality) is an essential requirement for greenhouse growing of high added value crops. Many areas have been abandoned due to the lack of water in sufficient quantities and of acceptable quality (salinity) in the Mediterranean Basin.

Drainage

The drainage conditions must be good, especially in regions of high rainfall. Places with a high water table must be avoided.

Soil characteristics

Whether cultivation is directly in the soil or in pots or containers, the soil must have properties appropriate for horticultural crops.

Pollution

For greenhouses located in urban areas, air pollution conditions must be evaluated, not only in terms of incidence on the plants themselves, but also with regard to residues deposited on the greenhouse, which can limit solar radiation (e.g. dust from factories) or damage the greenhouse cladding material.

Availability of space

Space may be required for future enlargement, auxiliary facilities (e.g. water basins for collection of rainfall water or storage of irrigation water) and buildings (e.g. handling, stores, offices).

Availability of labour

If local labour is not available, it is necessary to consider the costs inherent in acquiring labour.

Infrastructures

Proximity to transport networks (e.g. roads, railway), access to communication systems (e.g. telephone, internet) and availability of energy (e.g. gas, electricity) must all be considered.

Orientation

The position must be chosen to avoid shadows from hills or neighbouring buildings. It is necessary to adapt the shape and slope of the roof to dominant winds, while maintaining the objective of maximum light in the greenhouse.

GAP recommendations

Site selection:

- Production costs and yield quality are key factors when choosing the greenhouse site; they depend mainly on climate conditions determining the greenhouse microclimate.
- Transportation costs are a crucial factor, although greenhouse production has expanded to areas far from destination markets, thanks to improvements in communications and logistics.

Climate conditions:

Profitable and sustainable cultivation of the target crop requires strict selection of the region, on the basis of its climate conditions and the requirements of the selected horticultural crop, noting the following considerations:

- Solar radiation (and its year-round availability) and air temperature are the two main climate parameters to evaluate.
- In cold and mild winter climate areas, the greenhouse effect prevails and the main objective is temperature increase.
- In tropical and subtropical areas, the windbreak effect (protection from strong winds), the umbrella effect (protection from heavy rains) and the shading effect (protection from high radiation) prevail.
- In arid and semi-arid regions, the oasis effect (raising air humidity and limiting high temperatures in a well-watered crop) prevails: there is increasingly widespread use of screens instead of plastic films as cladding material.

Market identification, establishment of distance, production planning (vegetables, fruits or ornamentals), knowledge of strategy to meet climate requirements:

- The best site offers the best climate conditions with the lowest production costs, with special attention to the availability of labour and inputs (water quality, electricity, communications etc.), and the distance to markets (transportation costs).
- Markets demand year-round production (not always possible in the Mediterranean area in a passive climate control greenhouse).
- There are two strategies for meeting climate requirements: invest in high-tech greenhouses which avoid strong dependence on the outdoor climate; or grow in two or more locations with complementary harvesting periods, enabling a continuous and coordinated year-round supply to markets.

GAP recommendations (cont.)

Region selection on the basis of climate conditions and crop requirements:

- Solar radiation is the first climate parameter to be evaluated, in particular year-round availability.
- Other important parameters are soil temperature (linked to air temperature) and, to a lesser extent, wind, rainfall and air composition (humidity and CO₂).
- The most commonly grown species in Mediterranean greenhouses are vegetables with medium thermal requirements (tomato, pepper, cucumber, melon, watermelon, marrow, green bean, eggplant etc.).
- Suitable species are warm season crops, adapted to average ambient temperatures ranging from 17 to 28 °C, and with limits of 12 °C (minimum) and 32 °C (maximum) (Nisen *et al.*, 1988). They are sensitive to the cold and suffer irreversible damage with frosts.
- Minimum daily radiation requirements of these species are estimated at around 6 hours of light per day, totalling a minimum of 500–550 hours of light during the 3 shortest months of the year (November, December and January in the Northern Hemisphere; May, June and July in the Southern Hemisphere).
- Unless there is an imperious need (and very high selling prices), greenhouse production is not recommended in geographical areas with unsuitable climate conditions requiring notable and expensive artificial climate control.
- Given the impossibility of increasing, at a reasonable cost, natural radiation conditions (except in very sophisticated greenhouses and with high-value crops), greenhouse design and location must optimize the interception of solar radiation during autumn and winter.
- To raise low temperatures, the most common solution is to heat the greenhouse, but this is not always profitable. In some cases, a highly isolating system can avoid temperature drop at night (e.g. “lean-to greenhouses” in China).
- To avoid excessively high temperatures, the traditional and most economically viable method is the renewal of interior air by means of ventilation.
- Other important parameters for climate suitability are soil temperature (linked to air temperature) and to a lesser degree, wind, rainfall and air composition (humidity and carbon dioxide, CO₂). There are some differences between air temperature and plant temperature and also between parts of the plant, especially during daytime, depending on the radiation intercepted, the water transpiration and the air movement. The root temperature is assumed to be the same as the soil temperature.

CONCLUSIONS

Site selection is crucial for profitable and sustainable greenhouse production. The climate influences the type and level of greenhouse technology (structure and internal equipment for climate control) and subsequent crop production conditions, which in turn influence product cost and quality. The distance to markets, especially in export-focused production, can be a limiting factor for profitable greenhouse cultivation. An economic compromise between the investment costs of the greenhouses and equipment and their agricultural performance is necessary to produce proper quality commodities at a competitive level.

Greenhouse site selection – Summary of considerations

Topography: flat in width direction; main axes slope of 0–0.5 percent (never > 1–2 percent, which would need terracing)

Microclimate: not frequently fogged areas, no shadows from hills etc.

Protection from cold wind: windbreaks

Irrigation water: adequate quality

Soil characteristics

Flooded areas: avoid; build drainage if necessary

Air pollution: especially near cities

Expansion: space for future greenhouse or auxiliary buildings

Labour availability

Communications network

Orientation: prioritize light interception in winter, adapted if possible to dominant winds

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3. Greenhouse design and covering materials

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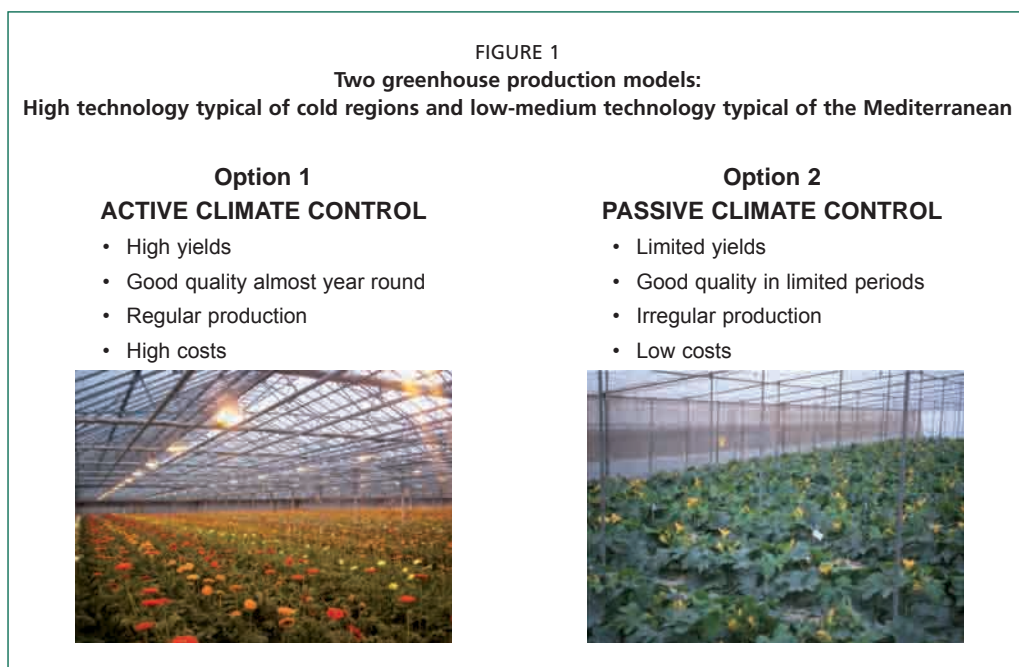
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INTRODUCTION

The energy crisis in the 1970s may be considered the main reason for the development of Mediterranean horticulture. As energy prices rose, the greenhouse surface area remained stable or decreased in countries with low winter temperatures, while it increased significantly in areas where heating requirements were much lower. Mediterranean horticulture benefited from the availability of abundant autumn and winter light and from the mild winter conditions resulting from the proximity of the growing areas to the sea (Castilla and Hernández, 2005). The energy scenario led to the establishment of two distinct production models (Figure 1):

- Cold countries adopted advanced greenhouse technology, increased light transmission, saved energy for heating and optimized all production means to achieve maximum yield; they used glass as covering material.
- Southern or Mediterranean greenhouses adapted to the local conditions, with moderate investments and little (if any) climate control system besides natural ventilation; this produced suboptimal conditions for plant production and as a consequence lower yields than high-tech greenhouses; they used mostly plastic film as covering material (Castilla, 2005).

This chapter discusses the most relevant issues related to greenhouse design and covering materials for good agricultural practices (GAP) in Mediterranean areas. Four main areas are dealt with: greenhouse types, plastic films as covering materials, insect-proof screens and greenhouse natural ventilation.



MAIN GREENHOUSE TYPES IN THE MEDITERRANEAN BASIN

Local-type greenhouses

These greenhouse types are normally very low-cost structures with little climate control besides natural ventilation; they are built with local materials (i.e. wood) and covered with polyethylene plastic film. The *parral*-type greenhouse is probably the most widely used in terms of surface area. In Almería (Spain) alone it covers approximately 27 000 ha (EFSA, 2009). The *parral* greenhouse is made of a vertical structure of rigid pillars (wood or steel) on which a double grid of wire is placed to attach the plastic film. As in other parts of the Mediterranean, the cost of materials obtained locally and the availability of installation expertise have been fundamental for greenhouse expansion.



Plate 1
Flat-roof greenhouses in Almería
(southern Spain)

Local-type greenhouses require a relatively low level of investment, making them suitable for farms operated by small growers. However, there are significant design-associated problems, such as lack of tightness, low radiation transmission in winter and, more importantly, lack of good natural ventilation as a result of:

- low ventilator surface area, due to a poor combination of side and roof ventilation and to the construction of excessively small roof vents, resulting from the grower's fear of sudden strong winds that may damage the ventilators.
- inefficient ventilator designs – for roof ventilation, flap ventilation is always preferable to rolling ventilators as it provides higher ventilator rates (almost three times greater airflow according to Pérez-Parra *et al.* [2004]).
- use of low porosity insect screens – insect-proof screens strongly reduce the air exchange rate.

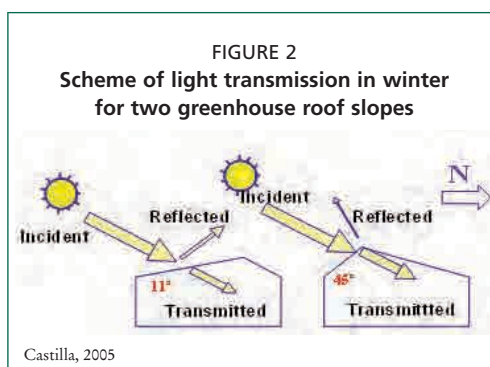
Good agricultural practices require good ventilation and light transmission. The lack of good ventilation in most local-type greenhouses can be compensated for by improved design of the ventilation systems. Light transmission depends on the properties of the covering material and the number of opaque supporting members, as well as the greenhouse geometry and orientation. In terms of roof slope, computer simulations show that during the winter, increasing the roof slope from 11 to 45° can increase daily light transmission by nearly 10 percent, since losses due to reflection are reduced. In practice, it is more useful to find a compromise between good light transmission and construction costs, and most new greenhouses have a roof slope of 25–30°.

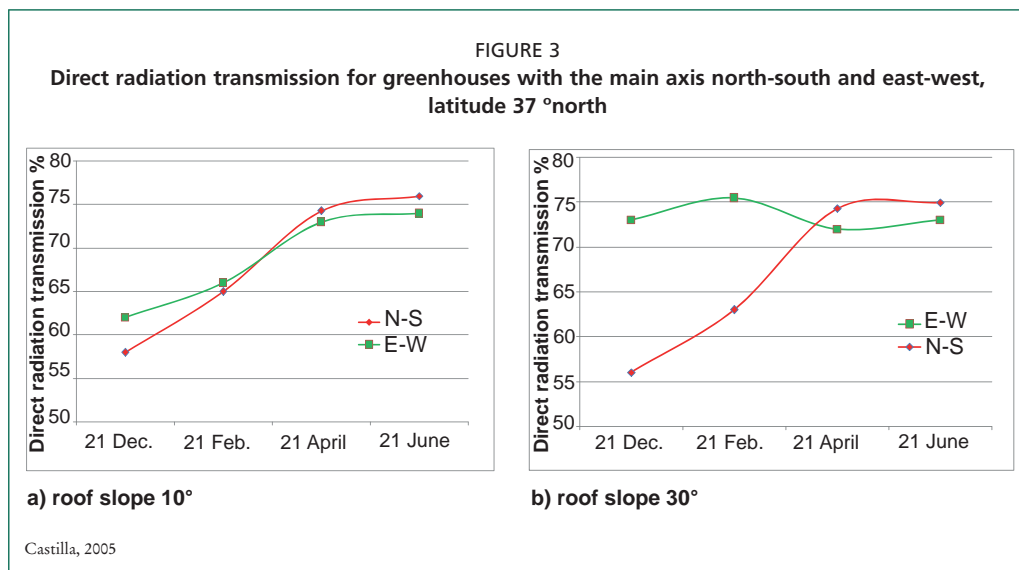
With regard to greenhouse orientation, there are two main factors that have to be balanced before choosing the best solution: light transmission and ventilation.

At Mediterranean latitudes (37°N), for greenhouses with a 10° roof slope, east to west (E–W) orientation has better transmission than north to south (N–S) during winter, while it has lower transmission in the summer; however, the differences are small (Figure 3a). For greenhouses with a 30° roof slope, the E–W greenhouse transmits approximately 13 percent more than the N–S greenhouse during the winter period (Figure 3b).

Therefore, in terms of light transmission, it is recommended to build the greenhouse with an E–W orientation. Nevertheless, light uniformity is better in N–S greenhouses since the gutter and ridge shadows change their position during the day as the sun moves. In some Mediterranean areas, greenhouses are E–W oriented, but the crop rows are N–S for greater crop uniformity.

With regard to ventilation, it is advisable to build the roof ventilators perpendicular to the prevailing winds to enhance the air exchange.





Plastic-covered industrial-type greenhouses

A large number of different greenhouse structures may be included in this group (pitched roof multi-span, asymmetric multi-span, saw-tooth, curved roof multi-span etc.). The arch-shaped multi-span system prevails among the industrial types, mostly clad with plastic film or, in some cases, with rigid or semi-rigid materials (preferably polycarbonate). The roof is often covered with plastic film, while the side and front walls are covered with semi-rigid plastics. These arch-shaped multi-span structures are normally made of galvanized steel and are preferred by the ornamental growers and nurseries. Multi-span structures are tighter than *parral*-type greenhouses and easier to equip with cooling, heating and/or computer control; such structures are very common in Israel.

In general, this group includes greenhouses with more efficient ventilation systems: the roof vents are usually larger than in the handmade greenhouses with



Plate 2

Arch-shaped multi-span greenhouses with single and double roof ventilators

at least one roof vent per span (double roof vents per span can also be found). In some cases, these structures may also have combined roof and sidewall ventilation. Sometimes roof ventilators are in an alternating mode facing one direction and the opposite direction, but there is no scientific evidence that this arrangement adds any advantage.

While arch-shaped multi-span greenhouses have many advantages, they are not free from problems. Condensation can occur in the upper inner part of the roof, resulting in dripping in humid and cold weather, usually during the early hours of the day. Attempts have been made to solve this problem by increasing the roof slope with pointed arches instead of circular, but this has not entirely eliminated the condensation.

Glasshouses

Glasshouses are the most commonly found greenhouse structures in cold parts of the Northern Hemisphere. They are usually built in very large compartments in order to lower cost per unit area, improve efficiency and reduce heat loss through the sidewalls; in the Netherlands the average glasshouse area was 1.5 ha in 2003 (Bunschoten and Pierik, 2003). They usually have only roof ventilators, which may be discontinuous (e.g. Venlo type, one-side mounted windows) or continuous. The relation between the ventilator area and the greenhouse covered area is often around 25 percent, which is close to the ASABE standards (ASABE, 1999).

The glasshouse area in southern European countries is limited, mainly because of the high investment costs. Glasshouses occupy less than 1 percent of the total greenhouse area in countries such as Spain. If glasshouses are to be constructed in climate areas warmer than northern Europe, ventilation must be improved. The combination of roof and sidewall ventilation ensures higher ventilation rates, both in windy conditions (Kacira *et al.*, 2004a) and in low or zero wind conditions with buoyancy-driven natural ventilation (Baeza *et al.*, 2009).



Plate 3
Venlo-type glasshouses

Greenhouse types – Conclusions and GAP recommendations

- Enhancing winter light transmission is an important good agricultural practice in Mediterranean areas: greenhouses must have a minimum roof slope of 25–30°.
- Local-type greenhouses, if properly designed, are suitable for mild climate areas. Their main advantage is their low investment cost; their principal disadvantage is the lack of climate control (mainly lack of ventilation).
- Avoid low roof slope greenhouses for better light transmission.
- If ventilation is of greater concern than light transmission, orient the greenhouse so that the vents are open towards the prevailing winds.
- Choose E–W orientation if there is no conflict with ventilation.
- Crop rows must be N–S for optimum light uniformity.
- Industrial-type plastic-covered greenhouses can modulate unfavourable external conditions. While recommended over the local-type greenhouses, their cost-benefit analysis could be worse than for local-type greenhouses in the short term.
- Glasshouses are excellent greenhouse structures, but they are not popular in southern European countries, mainly because of the high investment costs.

PLASTIC FILMS AS GREENHOUSE COVERING MATERIAL

A covering material is chosen for its optical and mechanical properties and on the basis of climate and location (Waaijenberg and Sonneveld, 2004). Good agricultural practices dictate that greenhouse plastic should have maximum solar transmission (so dust washes away easily and does not stick) and be opaque to long-wave radiation to reduce heat loss at night.

Greenhouse films are composed of polymers and additives. Polymers are the basic component, while additives provide a variety of different properties including infrared absorption/reflection and light diffusion. Greenhouse cladding films range in thickness from 80 to 200 μm . Film width is up to 20 m. Single layer or multilayer (typically three-layer) films are widely used in commercial production, but multilayer films are preferred as they combine the positive properties of their individual components (e.g. good mechanical resistance and good light transmission). The life span of greenhouse films has increased from 9 months during the 1950s to approximately 45 months today. Weathering depends on the photo-additives incorporated in the film as well as on the geographic location and the exposure of the film to pesticide treatments (Cepla, 2006).

Polymers and additives

Polymers are large molecules formed by the association of smaller units called monomers. The most common polymers used in horticulture are low density polyethylene (LDPE), ethylene vinyl acetate (EVA) and ethylene butyl acrylate

(EBA). These three polymers cover more than 80 percent of the world market. Other materials are also popular, such as PVC in Japan or linear low density polyethylene (LLDP) in the rest of the world. In comparison with glass, a property common to all plastic materials is their low density and therefore low weight (Table 1).

The low density and thickness of plastic materials is a great advantage in horticulture since it facilitates transportation, handling and installation. For example, 1 m² of LDPE film 200 µm thick weighs approximately 184 g; the same film made of PVC weighs about 260 g; while a glass pane 4 mm thick weighs 10 kg. The light weight and flexibility of the covering material allows a significant reduction in the size and number of the supporting members, making the greenhouse frame lighter compared with the glasshouse frame, and thus much cheaper.

Additives are an essential part of the covering materials. They are dispersed between the chains of polymer molecules without interacting chemically. Additives are used to facilitate the manufacturing of the film as well as to improve its performance under field conditions; the type and quantity of additive depends on which properties of the covering material need improving.

The two most common additives in horticulture are UV (ultraviolet) stabilizer additives and IR (infrared) absorbing additives. UV stabilizers absorb UV radiation or protect the polymer molecules. As a consequence, the film ages more slowly: indeed, the vast majority of plastic films in horticulture last more than one year and include UV stabilizer additives.

Good greenhouse film should block long-wave IR radiation (wavelength 0.7–4 µm) so as to reduce heat loss. So-called thermal films are particularly effective for increasing leaf temperature in passive, unheated greenhouses during clear nights. Polyethylene films are very transparent to long-wave IR radiation, therefore IR-absorbing additives are commonly used to improve the thermal properties of the films.

Properties of greenhouse plastic covering materials relevant to GAP

Clear films and diffusive films

In areas with clear skies and high solar radiation, direct radiation can cause leaf burning in greenhouse crops on warm days. New plastic films have been developed to increase the percentage of diffuse radiation in the greenhouse. Radiation is considered “diffuse” when it deviates more than 2.5° from the

TABLE 1
Density of different polymers used in horticulture

Material	Density (g/cm ³)
Low density polyethylene (LDPE)	0.915–0.930
Copolymer ethylene vinyl acetate (EVA)	0.920–0.930
Copolymer ethylene butyl acrylate (EBA)	0.920–0.930
Polyvinyl chloride (flexible) (PVC)	1.250–1.500
Polymethyl methacrylate (PMMA)	1.180
Polyester/Fibreglass	1.500–1.600
Glass	2.400

**Plate 4**

Covering greenhouse films: clear film (left); diffusive film (right)

**Plate 5**

Greenhouse covered with different plastic films

additives that increase electrical conductivity can be incorporated into the interior or on the surface of the film. Montero *et al.* (2001) reported that dirt accumulation reduced light transmission of a new PE plastic film by approximately 6 percent after 1 year of exposure in coastal Spain. EVA films are reported to lose more light transmission due to dust accumulation.

**Plate 6**

Anti-dripping film (right side)

direct incident radiation. The percentage of diffuse radiation to global radiation is known as turbidity. Increased turbidity results in greater light uniformity and higher yields in Mediterranean countries (Castilla and Hernández, 2007; Cabrera *et al.*, 2009). Diffusive light also has positive effects in northern countries such as the Netherlands. Hemming *et al.* (2008) compared the effect of diffusive glass against clear glass and concluded that more light was intercepted by the crop in diffuse treatment, especially by the intermediate leaf layers; thus assimilation was higher and cucumber production increased by approximately 8 percent.

Anti-dust films

Most polymers are poor electricity conductors, particularly prone to the accumulation of static electricity when two surfaces are rubbed against each other or when there is friction caused by the wind. As a consequence, most plastics attract dust. To reduce static electricity, some

Anti-drip films

Water vapour condenses on the cold inner cover surface forming small droplets of liquid water. This has negative consequences on light transmission; some condensation studies have reported PAR (photosynthetically active radiation) transmission losses close to 20 percent for incident radiation angles bigger than 15°. This loss in light transmission varies with drop size: large drops reduce transmission less than small drops due to the different

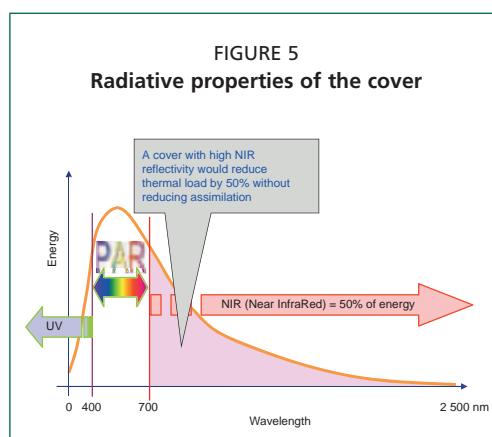
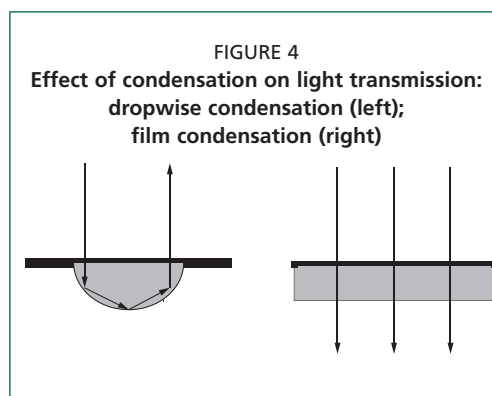
contact angle of the drop with the plastic (Castilla, 2005). Moreover, condensation can fall onto the crop fostering development of fungal diseases. Anti-drip additives modify the surface tension of water, eliminate droplets and form instead a continuous thin layer of water (Figure 4).

There are several methods for producing a continuous layer of condensed water, such as treatment of the film surface or oxidation of the polymer surface, but the most efficient method for agricultural films is the incorporation of additives during the manufacturing process. However, such additives migrate towards the plastic surface getting washed away by rain or condensation, and anti-drip properties are usually lost before the end of the plastic's life span. One solution is to use multilayer plastics where one of the central layers is used as a reservoir of anti-drip additives which continuously replace the additives lost through washing.

NIR-blocking plastic materials

Only about half of the energy that enters a greenhouse as sun radiation is in the wavelength range useful for photosynthesis (PAR: photosynthetically active radiation). Nearly all the remaining energy fraction is in the near infrared range (NIR): it warms the greenhouse and crop and contributes to transpiration, none of which is necessarily always desirable (Figure 5).

Some new plastic film prototypes contain NIR-reflecting pigments with several concentrations. A significant reduction of the sun radiation energy content in the NIR range is thus possible without much reduction in the PAR range. The effectiveness of NIR films on the reduction of greenhouse air and crop temperatures and their effects on crop yield and quality depends on a number of factors, such as the amount of NIR filtered by the film, the ventilation capacity of the greenhouse, the crop density and the canopy transpiration. The desk study of Hemming *et al.* (2006) showed that under Dutch conditions, mean air temperature in a Venlo-type greenhouse could be reduced by about 1 °C during the summer months, but the NIR film increased energy consumption for heating in the winter months. Field tests conducted in southern Spain produced

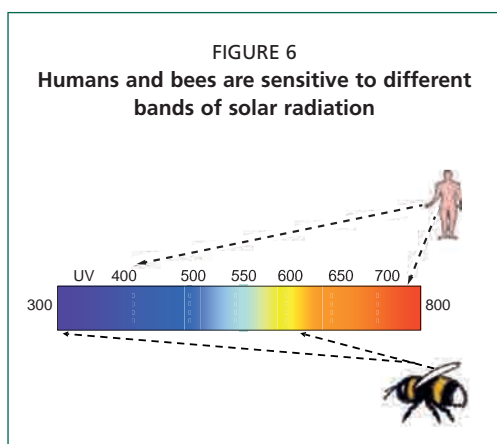


more optimistic results – temperature reductions of up to 4 °C during summer months, and increased yield and quality of a pepper crop (García-Alonso *et al.*, 2006).

Three application methods are possible for commercially available NIR-selective filters: as permanent additives or coatings of the cover; as seasonal “whitewash”; and as movable screens. The combination of external climate conditions and type of greenhouse determines the most appropriate form of application in a given location. Some of these factors have been taken into account in the study by Kempkes *et al.* (2008), which quantifies the expected benefits in terms of inside climate. They show that year-round filtering of the NIR component of sun radiation is unlikely to increase productivity, even in mild winter climates, unless the reflected energy can be used.

Blocking UV radiation to limit harmful insect activity

The term “UV blocking” is applied to plastic films and nets made by various manufacturers with different capacities to absorb sunlight below 380 nm. The two most harmful insects for crop production in Mediterranean greenhouses are *Bemisia tabaci* (whitefly) and *Frankliniella occidentalis* (thrips), mainly because both are effective vectors for the transmission of virus diseases. The ability of these insects to move is associated with UV radiation; hence, by using plastic materials that absorb UV radiation, virus-disease transmission can be mitigated (González *et al.*, 2003). The subject is dealt with in more detail in the section on insect-proof screens.



However, reducing UV radiation also limits the role of beneficial insects used for pollination, such as *Apis mellifera* (bees) and *Bombus terrestris* (bumblebees). Field tests in the Mediterranean area show that insect pollination is not affected, provided that enough time is given to the beehives to get accustomed to the low UV levels within the greenhouse. It must also be pointed out that blocking UV-radiation may have detrimental effects on secondary metabolism, i.e. plant defences and micronutritional quality of products (subjects not discussed in this chapter).

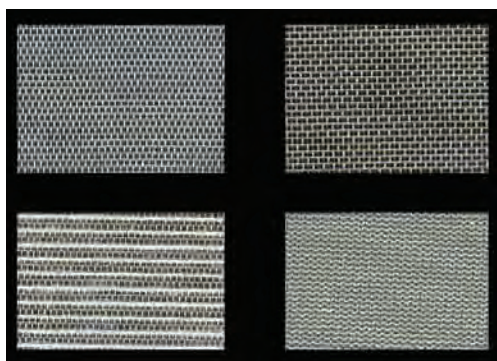
Plastic covering materials – GAP recommendations

- Multilayer rather than single-layer films are recommended since they allow addition of the positive properties of each of the components that form the film.
- Diffusive films are preferred over clear films because they improve light uniformity and increase light interception by the crop.
- EVA films on the outer surface of the cover are to be avoided in dusty areas due to higher losses in light transmission.
- Anti-drip films improve transmission and reduce dripping from the inner surface, but usually lose their anti-drip properties before the end of their life span.
- In Mediterranean climates, a permanent NIR filter may have useful applications during the summer, but could be detrimental during the winter.
- Movable screens or seasonal whitewashing with NIR filter have good potential; this technique is currently under investigation.
- UV-blocking films are a promising technique to reduce pest infestation, but their commercial availability is still limited.

INSECT-PROOF SCREENS FOR GOOD AGRICULTURAL PRACTICES

In the Mediterranean and southeastern Europe most greenhouses are equipped with ventilation openings to provide good microclimate conditions for plant growth. Unfortunately, these vents serve also as a major port of entry for pests and, as a consequence, growers are forced to cover the vents completely and permanently with fine mesh screens to prevent pest invasion. Since the pests can be very small (e.g. whiteflies and thrips), very fine mesh screens are required to prevent their entry; these screens impede ventilation and, in some cases, reduce light transmission (Bethke *et al.*, 1994; Klose and Tantau, 2004; Teitel, 2001). Moreover, the targeted insects are most abundant during the warm and hot seasons when effective ventilation is essential for avoiding stressful conditions for both crop plants and workers (Teitel, 2001).

Screens are characterized by their porosity (ratio between open area and total area), mesh size, thread dimension (diameter or thickness), texture (woven, knitted, woven/knitted), colour, light transmission/reflection and resistance to airflow. Most insect-proof screens have square or rectangular openings and are made of monofilament threads. They are generally characterized by the term “mesh”, which is the number of open spaces per inch in each direction, delineated by the threads (e.g. a 50-mesh screen has 50 spaces per inch in either the warp or the weft direction). Usually, screens are a product of weaving: a set of threads (the warp) stretched in a frame, or loom, are bound together to form a

**Plate 7**

Samples of insect proof screens

Top: simple geometries, round monofilament threads, rectangular holes

Bottom right: complex geometry, round monofilament threads, irregular hole shapes (areas hard to measure)

Bottom left: complex geometry, vertical threads round monofilament, horizontal threads some round monofilament, others with lashes

coherent fabric by means of other threads (the weft) introduced at right angles to the warp threads and passing in a determinate order over and under them. In Europe, screens are generally characterized by the number of spaces per centimetre in each direction (e.g. a 10*20 screen has 10 spaces per centimetre in one direction and 20 in the other direction). Nevertheless, there could still be difficulties in characterizing a screen with a complex weave (i.e. where the threads do not form openings of a simple rectangular or square shape or when the threads are not a round monofilament fibre with an easily measured diameter). For such screens, there is still no reliable method of documentation; they can only be characterized with laboratory tests relating pressure drop on the fabric as a function of upstream velocity.

Effect of insect-proof screens on ventilation

An important consideration when designing a screen installation is the effect that screen materials have on airflow through the openings. It has been well documented that screens increase the pressure drop on the openings, which results in reduced ventilation. It is also well known that the pressure drop on screens is mainly a function of screen porosity. For a woven screen made of a monofilament thread and with a simple texture, it is possible to calculate the porosity (ε) from the geometric dimensions of the screen:

$$\varepsilon = \frac{(l - d)(m - d)}{ml} \quad \text{Eq. 1}$$

where:

l and m are the distance between the centres of two adjacent weft and warp threads, respectively

d is the diameter of the threads

This porosity relates to an orthogonal projection of the screen. Teitel (2007), on the basis of data from literature, suggested the following correlation:

$$\Delta T_{sw} = \Delta T_w (5 - 4\varepsilon) \quad \text{Eq. 2}$$

to estimate the effect screens on the vents have on temperature difference between greenhouse and ambient air with screens (ΔT_{sw}) and without screens (ΔT_w). Nevertheless, it should be kept in mind that Equation 2 provides

only a rough estimate of ΔT_{SW} , since the relationship between the temperature difference with and without a screen is dependent on greenhouse type, crop, weather and the exact location where the inside air temperature was measured. The change of $\Delta T_{SW} / \Delta T_W$ with the porosity is shown in Figure 7: as the value of porosity increases, the ventilation rate increases and the inside/outside temperature difference decreases.

From the study conducted by Pérez-Parra *et al.* (2004), it can be deduced that an anti-thrips screen can reduce ventilation by approximately 60–70 percent while an anti-aphid screen can reduce it by 40 percent.

In recent years, methods have been developed to improve the unfavourable conditions in the greenhouse due to insect screens:

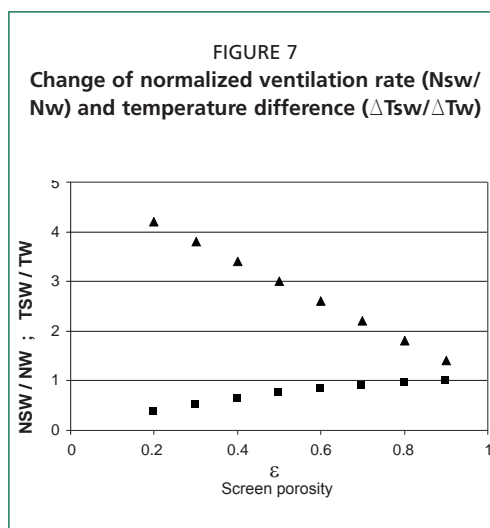
- Incorporation of optical or electrical insect deterrents with insect screen, enabling growers to use low mesh screens while maintaining a high level of protection from pests.
- Removal of insect screens from vents when the risk of pest invasion is low.
- Maximization of screened area.

Photo-selective screens, colour effects and other modifications

There are two possible explanations for the mechanism by which photo-selective screens provide protection against arthropod pests:

- The light inside the greenhouse contains less UV light and therefore becomes “invisible” to the pest. There are reports of thrips and whiteflies preferring to move into UV-containing environments (Antignus *et al.*, 2001; Costa *et al.*, 2002; Doukas and Payne, 2007).
- Higher levels of reflected sunlight deter pest landing. Reports indicate that thrips are repelled by high UV reflectance (Matteson *et al.*, 1992; Vernon and Gillespie, 1990). Furthermore, total light reflection by aluminium mulches and aluminium-coloured screens also reduces pest infestations in both open fields and protected crops (Greer and Dole, 2003).

In recent years crops have been grown under coloured nets to promote beneficial physiological responses (Shahak *et al.*, 2008). Nets used are yellow or blue, colours known to attract whiteflies and thrips, respectively. The risk for pest infestation under these nets is equal to or lower than the risk under black nets.



While pests prefer landing on the coloured nets, they remain there for a long time; this form of arrestment response (Bukovinszky *et al.*, 2005) makes the pests less likely to infest the plants underneath these nets. Adding “arrestment colours” to insect screens is likely to reduce the risk of pest invasion in the greenhouse.

A promising new electrostatic insect-proof screen (electric dipolar screen) was developed by Tanaka *et al.* (2008). This screen prevented all adult whiteflies from passing through sparse screens with spaces of up to 30 mm between the wires. Tomato plants grown under the electrostatic screen had no whitefly infestation, while there were heavy infestations of plants under a similar uncharged screen.

Removing insect screen from vents when the risk of pest invasion is low

Optimal climatic conditions in the greenhouse are often maintained by closing and opening windows and vents. However, insect screens covering windows and vents are not regulated in response to changes in the risk of invasion by pests. Greenhouse ventilation is likely to be improved if ventilation openings are uncovered when there is no risk of pest invasion (Ben-Yakir *et al.*, 2008). In the fall, when the whitefly population peaks, over 97 percent of whiteflies entered the greenhouse between 7.00 and 13.00 hours (Teitel *et al.*, 2005). Thus, the risk of whitefly entering greenhouses in the afternoon and at night is negligible. The flight of onion thrips and western flower thrips was studied using sticky pole traps and similar traps mounted on wind vanes. For most of the year, about 85 percent of the thrips were caught in the morning and 10 percent at dusk (Ben-Yakir and Chen, 2008). Mateus *et al.* (1996) also reported that *F. occidentalis* in a pepper greenhouse had two daily flight peaks: one in the morning and one in the afternoon. Flight time was correlated with periods of low wind speed and thrips were seldom caught with wind > 10 km/h. It has been reported that thrips in the genus *Frankliniella* are deterred from taking off when wind speed exceeds 9 km/h (Lewis, 1997). Both whiteflies and thrips are not likely to enter protected crops during the hot and windy afternoon hours or at night. Therefore, insect screens may be removed from vents during those times. Nevertheless there is no general agreement between experts on the convenience of removing insect screens, so at present it cannot be considered a general GAP.

Maximizing the screened area

One method for increasing ventilation in multi-span greenhouses with roof openings on which screens are mounted is to increase the maximum angle at which the flap can be opened. Another option is to fit the frames of the openings with pre-formed concertina-shaped screens that unfold as the ventilators open and then fold up again when they close (Plate 8). Teitel *et al.* (2008) have shown that a concertina-shaped screen allows higher airflow (an increase of about 25%) when compared with a flat screen under similar pressure drops across the screen. Recent computational fluid dynamics (CFD) simulations, carried out by Teitel (unpublished data) suggest that concertina-shaped screens may allow much higher

**Plate 8**

Concertina-shaped screens installed in the roof openings of a Venlo greenhouse

ventilation rates (depending on the ratio between the concertina and flat screen area).

In addition to the effects on insect penetration and the ventilation rate, the screens reduce light transmission into the greenhouse by creating strips of shadow on the crop when they are installed on roof openings. In dusty regions the shadow effect may worsen with time due to the accumulation of dust on the screens. Klose and Tantau (2004) found that although screens with the largest distance between adjacent threads had the highest light transmission, screens with the smallest distance did not necessarily have the lowest. Hence, they concluded that light transmission was influenced by additional parameters, such as the structure of the threads and, of course, accumulation of dirt.

Insect-proof screens – GAP recommendations

- Insect-proof screens produce a major reduction in ventilation; it is estimated that an anti-thrip screen can reduce ventilation by 60–70 percent while an anti-aphid screen can reduce it by 40 percent.
- Ventilation reduction can be mitigated by increasing the ventilation surface and by increasing the screen area as in concertina-shaped screens.
- Screens with a smaller thread diameter are preferred as they are more porous and ventilate better.
- Photo-selective screens provide extra protection against pests. Moreover, adding “arrestment colours” (e.g. blue and yellow) is likely to reduce the risk of pest invasion in the greenhouse.

TRENDS IN NATURAL VENTILATION

Proper ventilation performance is crucial for greenhouses in both humid winter climates and hot summer conditions. The ventilation process contributes to optimal control of air temperature, humidity and concentration of gases within the greenhouse. Thus, photosynthetic and transpiration activities of plants are regulated properly and crop quality is improved. Given the advantages – low maintenance, low operational costs and reduced noise – natural ventilation is used by the great majority of growers in the Mediterranean area since it is the most inexpensive way to regulate greenhouse internal microclimate area. However, control of airflow with natural ventilation is limited. Therefore, it is necessary to analyse natural ventilation properly and increase ventilation efficiency.

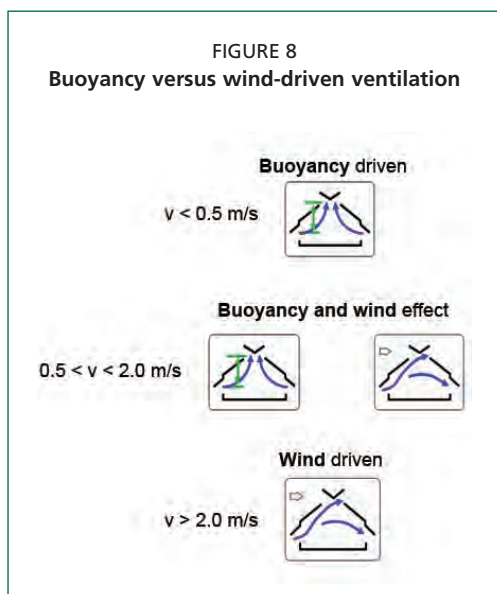
The driving force for natural ventilation is the pressure difference across the ventilation openings caused by wind and/or thermal effects.

Wind-driven ventilation

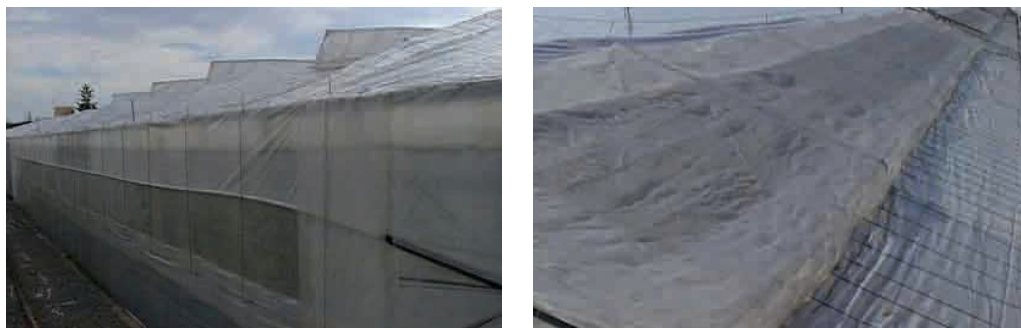
When the wind blows around a greenhouse, the wind field generates pressure distribution through the greenhouse. Moreover, wind has a fluctuating character that creates a fluctuating pressure difference over the openings; the mean difference in pressure and the fluctuating pressure difference are responsible for the airflow through the greenhouse ventilators (Bot, 1983; de Jong, 1990). There are claims that air exchange is proportional to outside wind velocity.

Thermally driven ventilation

Under calm conditions, buoyancy forces (differences between inside and outside air densities) are the driving mechanism for ventilation, but the effect of thermal buoyancy on ventilation is of fundamental interest when there is almost no wind (Baeza *et al.*, 2009). It has been reported that winds over 2 m/s dominate the ventilation process, making the effect of air temperature difference negligible (Bot, 1983; Papadakis *et al.*, 1996; Mistriotis *et al.*, 1997a). Buoyancy-driven ventilation is more important when wind speeds are below 0.5 m/s (Baeza *et al.*, 2009). Generally speaking, for intermediate and higher wind speeds, where $0.5 \text{ m/s} < u < 2.5 \text{ m/s}$, ventilation is driven mostly by wind effect and with some influence of buoyancy (Mistriotis *et al.*, 1997a) (Figure 8).



Natural ventilation can be achieved by opening windows at the top of the

**Plate 9**

Flap ventilators on the roof and rolling ventilators on the side wall (left)

Rolling ventilators on the roof (right)

greenhouse and/or at the sidewalls. The number and size of the windows and the mechanisms for window opening vary, with many different arrangements used in glasshouses and plastic-covered houses. Ridge openings can be classified as “continuous” or “non-continuous” and they are usually on both sides of the ridge, although hoses with openings on one side only are also constructed. Roof vents are either fixed or fully automatic (movable roof vents). A fixed overlapping vent on a gable ridge provides ventilation while preventing penetration of rain and hail. Movable roof vents may be formed by: film roll-up from gutter to ridge; ridge-hinged arched vents; vertical openings at the centre of the arch running the entire length of the roof; vertical roof openings starting at the gutters and extending to a height of about 1 m; or vertical openings at the centre of the arched roof running the entire length of the roof. The position and hinging of the vent at the ridge are the basis of a better evacuation of the hot and humid air which builds up at the top of the greenhouse. In Venlo greenhouses, the ventilators in most of the houses are hinged from the ridge and extend halfway to the gutter or as far as the gutter. The idea is to provide a large opening area especially in warm and humid areas. Recent greenhouse designs provide retractable roofs.

Side ventilation is usually achieved by rolling up curtains with a central mechanism operated manually or by an electric motor. Mechanisms that open the side vents from bottom to top (or vice versa, although less common) are available. Side openings with flaps hinged from the top are also used; however, they are more common in glasshouses than in plastic-covered houses. Flap ventilators are more efficient than rolling ventilators, particularly under moderate wind conditions.

Airflow characteristics under wind-driven ventilation

The latest advances in ventilation are based on numerical models, using computational fluid dynamics (CFD) to solve the governing equations. By using CFD models it is possible to obtain detailed vector fields of air velocity in and around the greenhouse, or precise fields of temperature, humidity or other variables relevant to greenhouse climate studies.

In order to better understand greenhouse ventilation, leeward and windward ventilation are examined in detail below. Windward ventilation is preferred to leeward ventilation for greenhouses located in warm areas, since windward ventilation clearly increases the ventilation rate (Pérez-Parra, 2002). Nevertheless, the internal climate is generally less uniform with windward ventilation.

Windward ventilation

The external air is “captured” by the vent opening of the first span. This results in an internal flow with the same direction as the external air. The first windward roof ventilator has the most significant effect on the intensity of air exchange and internal airflow (Baeza, 2007).

Leeward ventilation

The external wind follows the windward roof of the first span and accelerates along the roof. The external flow separates from the greenhouse structure at the ridge of the first windward span and creates an area of low speed above subsequent spans. Greenhouse air exits the greenhouse through the first roof ventilator, creating an internal flow which is opposite the external flow. As for windward ventilation, the first ventilator plays the leading role in the air exchange process (Flores, 2010).

This is the general outline of the air pattern for windward and leeward ventilation, but in very wide greenhouses the internal airflow may be different. Mistriotis *et al.* (1997b) and Reichrath and Davies (2001) have detected the occurrence of a dead zone with low velocity at approximately 60 percent of the total glasshouse length for a very large Venlo-type greenhouse (60 spans) under similar pure leeward ventilation conditions. Similarly, windward ventilation in wide greenhouses produces two clearly differentiated circulation areas. The zone where both circulation cells meet is a dead zone with low air movement and high temperature. The general recommendation is, whenever possible, to limit greenhouse width to approximately 50 m (Baeza, 2007) and to leave a separation between adjacent greenhouses to allow hot air to escape.

Sidewall ventilation

Sidewall ventilation is similar to windward roof ventilation with respect to the airflow pattern, since for sidewall ventilation the external air also enters the greenhouse through the windward side and passes along the greenhouse width. Kacira *et al.* (2004a) conducted CFD simulations to investigate the effect of side vents in relation to the span number of a gothic greenhouse with a continuous roof vent on the leeward side of each ridge. Compared with roof ventilation only, it was found that when both sides were fully open the ventilation rate increased strongly. The study showed that the maximum greenhouse ventilation rate was achieved when both side and roof vents were used for ventilation. Without buoyancy effect in the computations, the ventilation rate increased linearly with the external wind speed. The ratio of the opening of the ventilator area to the greenhouse

floor area (9.6%) was found to be small compared with the recommended ratios of 15–25 percent. The results showed that a significant reduction in ventilation rate was determined as the number of spans was increased (from 6 to 24) and an exponential decay described the relationship between the ventilation rate and the number of spans.

Sidewall ventilation may help reduce the area of the dead zone with high temperatures typical of wide greenhouses. However, side ventilation is not accepted by many growers who are reluctant to open the sidewall and roof ventilators in the windward direction, as they want to protect their crops and greenhouse frames from potential wind damage. For this reason, side deflectors are currently being put into practice (Baeza, 2007) and simple mechanisms to protect ventilators against wind gusts are becoming popular in Mediterranean countries.

Suggestions to improve natural ventilation

Use of deflectors

As pointed out by Sase (2006), in many types of ventilator the incoming air mainly follows the inner surface of the roof and creates a crossflow above the crop without mixing with the air in the crop area. To avoid this problem, the use of screens or deflectors to redirect the air stream is recommended. Nielsen (2002) offered a method to direct the passing airflow at the hinged ridge vents into the crop space (Figure 9): using a 1-m high vertical screen mounted to the ridge, improvements were achieved in the air exchange in the plant zone of about 50 percent on average.

Kacira *et al.* (2004b) evaluated the optimization of the traditional vent configuration for a two-span glasshouse for better air renewal especially in the plant canopy zone. The study was based on three-dimensional numerical

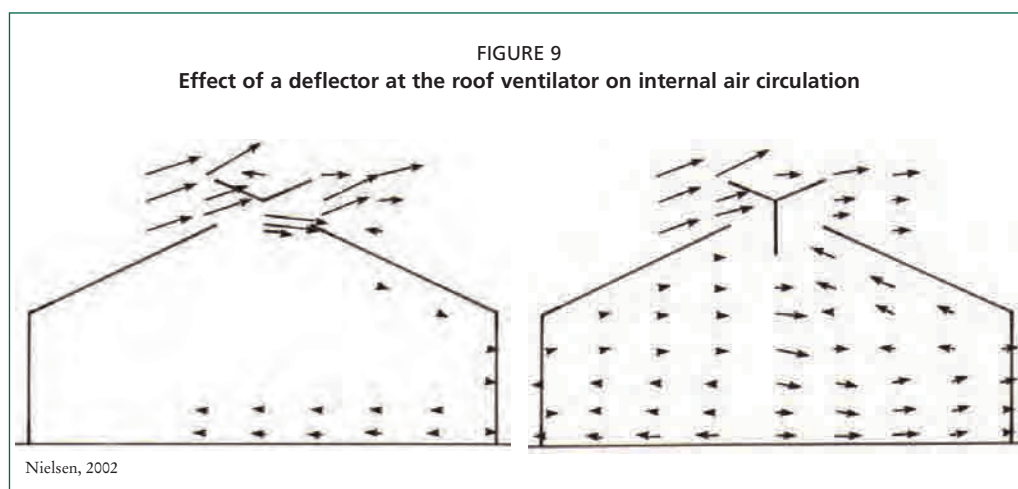
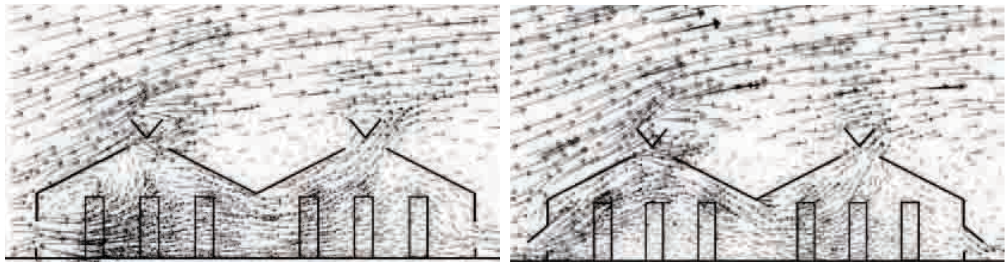


FIGURE 10
The effect of side vent configuration on the canopy zone ventilation and air exchange process
Roll up side vents (left); butterfly type side vents (right)



simulations using the CFD approach. The study evaluated both roll-up and butterfly-type side vent openings and various roof vent opening configurations (Figure 10). The maximum greenhouse ventilation rates were achieved when roll-up side vents were used in the sidewalls, and both side and roof vents were fully open. Use of the roll-up side vent considerably improved the ventilation rate in the plant canopy zone. This showed that ventilation in the plant canopy zone was significantly affected by the internal airflow patterns caused by different vent configurations (Figure 11).

Kacira *et al.* (2004b) demonstrated the importance of analysing the ventilation rates in the plant canopy zone as well as above the canopy. For example, under the same external wind speed and plant existence conditions, the ventilation rates in

FIGURE 11
Effects of external wind speed and vent configuration on ventilation rates
of greenhouse and plant canopy

Ventilation rate for greenhouse (m ³ m ⁻² min ⁻¹)								
Wind speed (m s ⁻¹)	Case 1	Case 2	Case 3	Case 4	Case 5	Case 6	Case 7	Case 8
0.5	1.54	0.59	1.91	0.84	1.47	1.49	1.63	1.46
1.0	3.16	1.21	3.95	1.77	3.16	3.15	3.49	3.00
1.5	4.78	1.84	6.03	2.72	4.86	4.83	5.38	4.56
2.0	6.40	2.46	8.11	3.68	6.59	6.53	7.29	6.12
2.5	8.02	3.09	10.20	4.64	8.32	8.23	9.20	7.68
Ventilation rate for plant canopy zone (m ³ m ⁻² min ⁻¹)								
0.5	0.69	0.43	1.84	0.99	1.41	1.43	1.56	2.11
1.0	1.50	0.98	4.25	2.50	3.43	3.43	3.74	4.74
1.5	2.29	1.55	6.64	4.09	5.45	5.44	5.93	7.35
2.0	3.07	2.17	9.02	5.68	7.47	7.45	8.11	9.95
2.5	3.86	2.80	11.38	7.27	9.49	9.44	10.29	12.55

Kacira *et al.*, 2004b

the greenhouse were found to be similar between the butterfly and roll-up curtain side vent configurations (Cases 1 and 3, Figure 11). However, the majority of the incoming air in the butterfly side vent cases did not reach the plant canopy zone. Conversely, the contribution of air entering the greenhouse from the windward roll-up curtain side vent for airflow uniformity and the achievement of higher ventilation rates in the plant canopy zone were found to be significant. The overall data showed that the ventilation in the plant canopy zone was considerably affected by the internal airflow patterns caused by different vent configurations.

Changes in the greenhouse slope

Increasing the greenhouse roof slope has a positive effect on the ventilation rate. Baeza (2007) compared the air exchange rate and internal airflow of greenhouses with slopes ranging from 12° to 32°. According to this study, ventilation sharply increased with roof slopes of up to 25°, after which the increase in ventilation was rather small. The low slope does not only affect the ventilation rate but also the air movement inside the greenhouse. Most of the airflow entering through the windward vent on a gentle slope attaches to the greenhouse cover, while with steeper slopes part of the airflow contributes to the ventilation of the first span and part of it moves on to the following span decreasing the attachment effect observed for lower slopes.

Size and type of ventilators

Baeza (2007) analysed the effect of ventilator size on greenhouse climate. He increased the flap ventilator size from 0.8 to 1.6 m in the first two and last two spans while maintaining the regular size of 0.8 m in the central spans. For a ten-span greenhouse, the increase in ventilator size had a significant effect on the ventilation rate. Besides, air movement in the crop area was enhanced. As a consequence, the temperature field was more uniform, the temperature difference in relation to the exterior was reduced and the stagnant air areas (warm spots) were significantly fewer in number and smaller in size. This study suggested that the greenhouse climate can be improved by making modest investments only in ventilators located in the first and last spans, which are critical to the air exchange process.

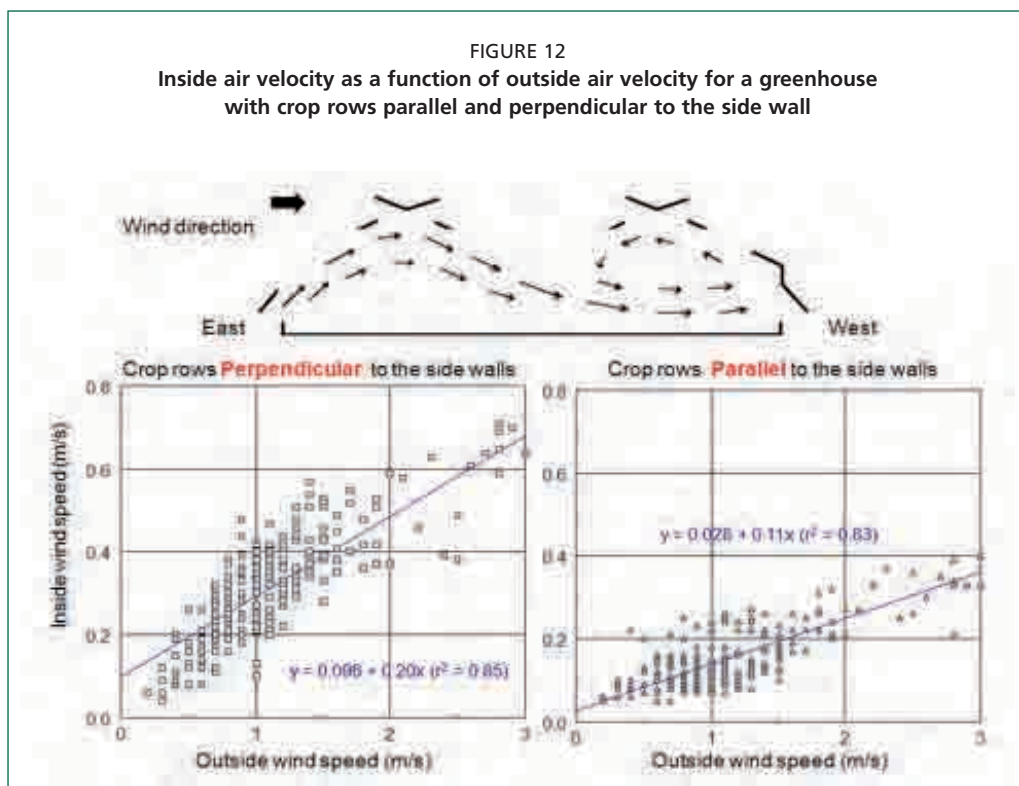
With regard to the ventilator type, Pérez-Parra (2004) compared flap ventilators and roll-up ventilators on the greenhouse roof under leeward and windward conditions. Flap ventilators were in all cases more effective at increasing ventilation rate than roll-up ventilators. Interestingly, the roll-up ventilator's performance was not affected by wind direction, while flap ventilators oriented windward side nearly doubled the air exchange of leeward flap ventilators.

Crop row orientation

Sase (1989) conducted a ventilation study to compare the effect of the crop rows perpendicular and parallel to the sidewalls. As seen in Figure 12, the inside air velocity in the greenhouse with perpendicular rows was nearly twice that of the greenhouse with parallel rows; the crop canopy is a porous medium that offers resistance to the airflow, so it is recommended that the aisle between rows be oriented in the direction of the internal airflow. Sase's study was conducted in a small greenhouse where side ventilation prevailed over roof ventilation. For roof ventilation only, the effect of the crop orientation may be less important, since in roof ventilated greenhouses there is strong air movement over the crop area at a higher speed than the air in the canopy zone (Flores, 2010).

New greenhouse designs with improved ventilation

All the recently developed knowledge can be put together to produce better ventilation designs. Upcoming greenhouse models relying on natural ventilation should be narrow enough (maximum width 50 m) to avoid excessive temperature gradients; furthermore, they should have larger ventilators, especially in the first span facing prevailing winds. They will incorporate screens or deflectors to redirect the airflow towards the crop area producing a homogeneous mixture



of the incoming and internal air, to have uniform growing conditions (Figure 13). Effective windward ventilation requires keeping an area between greenhouses free from obstacles. For proper ventilation, future greenhouse designs will not consider a single greenhouse, but a group or a greenhouse cluster, since the airflow in a greenhouse is affected by its surroundings.

Natural ventilation is the main method for greenhouse cooling, mainly because of the low energy consumption and reduced maintenance costs. However, natural ventilation relies on external conditions such as wind speed and direction and outside air temperature and humidity. Natural ventilation itself may not be sufficient to provide the desired environment under certain conditions. Thus, some other cooling techniques such as shading, mechanical ventilation or evaporative cooling, are used combined with natural ventilation. For a full discussion, it is necessary to consult the specific literature (Arbel *et al.*, 2006; Li *et al.*, 2006; Lorenzo *et al.*, 2004; Abdel-Ghany and Kozai, 2006; Abdel-Ghany *et al.*, 2006).

FIGURE 13
CFD study of the airflow pattern in a greenhouse with improved ventilation

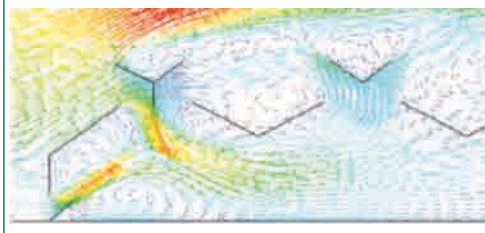


Plate 10
“Inversos” greenhouse. Prototype under evaluation. Fundacion Cajamar, Almería, Spain

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4. Greenhouse climate control and energy use

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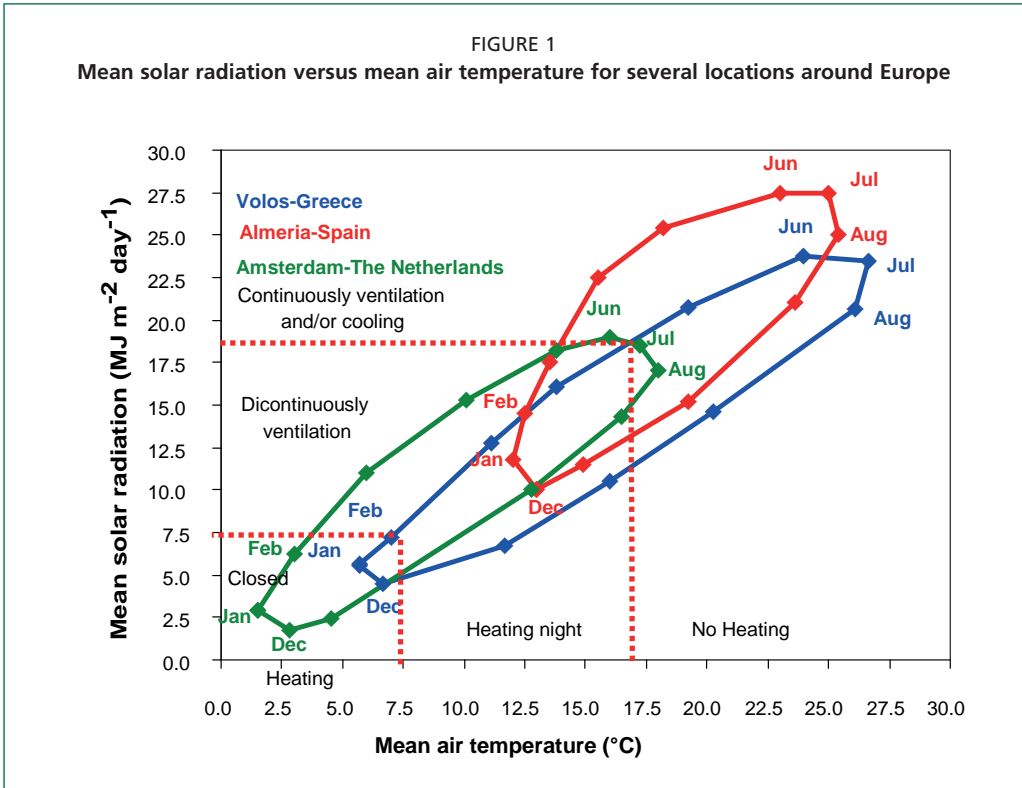
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DRIVING FORCES FOR GREENHOUSE CLIMATE CONTROL AND SUSTAINABLE ENERGY USE IN MEDITERRANEAN GREENHOUSES

All greenhouse cultivation systems, regardless of geographic location, comprise fundamental climate control components; depending on their design and complexity, they provide more or less climate control, and condition to a varying degree plant growth and productivity.

Air temperature – as well as solar radiation and air relative humidity – is one of the most important variables of the greenhouse climate that can be controlled. It conditions not only crop development and production but also energy requirements, which can account for up to 40 percent of the total production costs. The majority of plants grown in greenhouses are warm-season species, adapted to average temperatures in the range 17–27 °C, with approximate lower and upper limits of 10 and 35 °C. If the average minimum outside temperature is < 10 °C, the greenhouse is likely to require heating, particularly at night. When the average maximum outside temperature is < 27 °C, ventilation will prevent excessive internal temperatures during the day; however, if the average maximum temperature is > 27–28 °C, artificial cooling may be necessary. The maximum greenhouse temperature should not exceed 30–35 °C for prolonged periods. The climograph of some Mediterranean and north European regions is shown in Figure 1. In temperate climates, as in the Netherlands, heating and ventilation enable the temperature to be controlled throughout the year, while at lower latitudes, such as in Almería (Spain) and Volos (Greece), the daytime temperatures are too high for ventilation to provide sufficient cooling during the summer. Positive cooling is then required to achieve suitable temperatures.

The second important variable is humidity, traditionally expressed in terms of relative humidity. Relative humidity within the range of 60–90 percent has little



effect on plants. Values below 60 percent may occur during ventilation in arid climates, or when plants are young with small leaves, and this can cause water stress. Serious problems can occur if relative humidity exceeds 95 percent for long periods, particularly at night as this favours the rapid development of fungus diseases such as *Botrytis cinerea*. The increased interest in maintaining adequate transpiration to avoid problems associated with calcium deficiency (Plate 1)



Plate 1
Pepper fruit with BER symptoms associated with calcium deficiency

has resulted in humidity being expressed in terms of the vapour pressure deficit (VPD) or the moisture deficit, both of which are directly related to transpiration. Maintaining the VPD above a minimum value helps to ensure adequate transpiration and also reduces disease problems. During the day, humidity can usually be reduced using ventilation. However, at night, unless the greenhouse is heated, the internal and external temperatures may be similar; if the external humidity is high, reducing the greenhouse humidity is not easy.

Following the energy crisis of the early 1980s, when limited energy supplies led to the first significant rise in energy prices, greenhouse energy use became a major research issue. With the recent increased interest in global warming and climate change, the use of fossil fuels is again on the political agenda and many governments have set maximum CO₂ emission levels for various industries, including the greenhouse sector. There are two main ways to increase greenhouse energy efficiency:

- reduce the energy input into the greenhouse system; and
- increase production per unit of energy.

The challenge is to meet both needs: improved energy efficiency combined with an absolute reduction in the overall energy consumption and related CO₂ emissions of the greenhouse industry. Technological innovations must focus on energy consumption for the return to productivity, quality and societal satisfaction.

There are a range of greenhouse system technologies which can be adopted by growers to improve climate control and energy use. However, there are numerous obstacles and constraints to overcome. The existing technology and know-how developed in north European countries are generally not directly transferable to the Mediterranean: high-level technology is beyond the means of most Mediterranean growers due to the high cost compared with the modest investment capacity; and know-how from north European growers is often inappropriate for the problems encountered in the Mediterranean shelters (Plate 2).

Where these technologies may be adopted, it is necessary to train and educate Mediterranean growers. To this end, specific research and development tasks have been initiated by the research institutes and extension services of Mediterranean countries. The issues addressed in this paper concern the means and best practices by which Mediterranean growers can alleviate the climate-generated stress conditions that inhibit the growth and the development of crops during the long warm season in a sustainable and energy-friendly way.



Plate 2

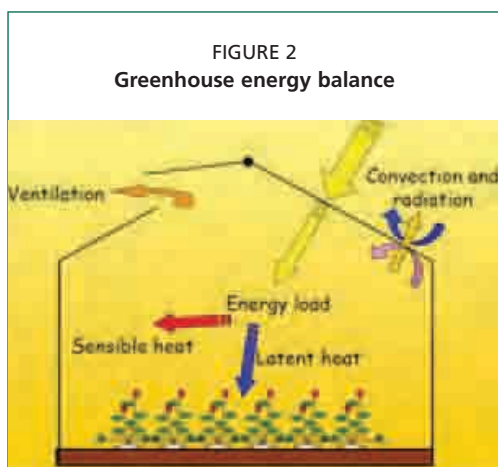
Internal view of parral (left, mainly found in Spain) and Venlo (right, mainly found in the Netherlands) type greenhouse

CLIMATE CONTROL

Ventilation cooling and shading

Removal of heat load is the major concern for greenhouse climate management in arid and semi-arid climate conditions. This can be achieved by:

- reducing incoming solar radiation;
- removing extra heat through air exchange; and
- increasing the fraction of energy partitioned into latent heat.



Shade screens and whitewash are the principle measures taken to reduce incoming solar radiation; greenhouse ventilation is an effective way to remove extra heat through air exchange between the inside and outside (when the outside air temperature is lower); and evaporative cooling is the common technique for reducing sensible heat load by increasing the latent heat fraction of dissipated energy. Other technological cooling solutions are available (heat pump, heat exchangers), but are not widely used, especially in the Mediterranean area because they require a high level of investment.

Ventilation

High summer temperatures mean that heat must constantly be removed from the greenhouse. A simple and effective way of reducing the difference between inside and outside air temperatures is to improve ventilation. Natural or passive ventilation requires very little external energy. It is based on the pressure difference between the greenhouse and the outside environment, resulting from the outside wind or the greenhouse temperature. If the greenhouse is equipped with ventilation openings (Plate 3), both near the ground and at the roof, hot internal air is replaced by cooler external air during hot sunny days when there is a slight wind. The external cool air enters the greenhouse through the lower side openings while the hot internal air exits through the roof openings due to the density difference between air masses of different temperature; the result is a lowering of the greenhouse temperature.

Sufficient ventilation is very important for optimal plant growth, especially in the case of high outside temperatures and solar radiation – common conditions during the summer in Mediterranean countries. In order to study the variables determining greenhouse air temperature and calculate the necessary measurements for temperature control, a simplified version of the greenhouse energy balance is formulated. Kittas *et al.* (2005) simplify the greenhouse energy balance to:



Plate 3
Different types of ventilation opening

$$Va = \frac{0.0003 \tau Rs, o - max}{\Delta T} \quad \text{Eq. 1}$$

where:

V_a is the ratio Q/A_g , Q is the ventilation flow rate ($\text{m}^3 [\text{air}] \text{s}^{-1}$)

A_g is the greenhouse ground surface area (m^2)

τ is the greenhouse transmission coefficient to solar radiation

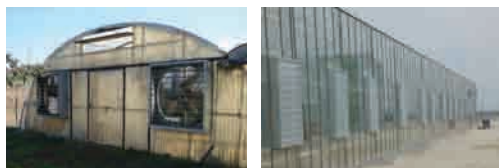
$R_{s,o-max}$ is the maximum outside solar radiation (W m^{-2})

ΔT is the temperature difference between greenhouse and outside air ($^{\circ}\text{C}$)

Using Equation 1, it is easy to calculate the ventilation requirements for several values of $R_{s,o-max}$ and ΔT . For the area of Magnesia, Greece, where values of outside solar radiation exceed 900 W m^{-2} during the critical summer period (Kittas *et al.*, 2005), a ventilation rate of about $0.06 \text{ m}^3 \text{ s}^{-1} \text{ m}^{-2}$ (which corresponds, for a greenhouse with a mean height of 3 m, to an air exchange of 60 h^{-1}) is needed in order to maintain a ΔT of about $4 \text{ }^{\circ}\text{C}$.

The necessary ventilation rate can be obtained by natural or forced ventilation; ventilators should, if possible, be located at the ridge, on the sidewalls and the gable. A total ventilator area equivalent to 15–30 percent of the floor area was recommended by White and Aldrich (1975); over 30 percent, the effect of additional ventilation area on the temperature difference was very small.

Some systems, including exhaust fan and blower, can supply high air exchange rates when needed. These simple and robust systems significantly increase the rate of air transfer from the greenhouse; consequently, the inside temperature can be kept at a level slightly above the outside temperature (Plate 4).

**Plate 4**

Fans for greenhouse forced ventilation

**Plate 5**

Insect-proof screen in roof opening

(albeit less homogeneous) around the canopy. Many researchers also studied the effects on greenhouse microclimate of insect-proof screens in roof openings (Plate 5). Fine mesh screens obstruct the airflow, resulting in reduced air velocity and higher temperature and humidity, as well as an increase in the thermal gradients within the greenhouse (Katsoulas *et al.*, 2006).

Shading

Natural or forced ventilation is generally not sufficient for extracting the excess energy during sunny summer days (Baille, 1999), and other cooling methods must be used in combination with ventilation. The entry of direct solar radiation

**Plate 6**

Thermal screen used for energy saving and greenhouse shading

The principle of forced ventilation is to create airflow through the house. Fans suck air out on one side, and openings on the other side let air in. Forced ventilation by fans is the most effective way to ventilate a greenhouse, but it consumes electricity. It is estimated that the electrical energy requirements for ventilation of a greenhouse located in the Mediterranean are about 70 000 kWh per greenhouse ha.

Kittas *et al.* (2001) studied the influence of the greenhouse ventilation regime (natural or forced ventilation) on the energy partitioning of a well-watered rose canopy during several summer days in warm Mediterranean conditions (eastern Greece). When not limited by too low external wind speed, natural ventilation could be more appropriate than forced ventilation, creating a more humid and cooler environment

around the canopy. Many researchers also studied the effects on greenhouse microclimate of insect-proof screens in roof openings (Plate 5). Fine mesh screens obstruct the airflow, resulting in reduced air velocity and higher temperature and humidity, as well as an increase in the thermal gradients within the greenhouse (Katsoulas *et al.*, 2006).

through the covers into the greenhouse enclosure is the primary source of heat gain. The entry of unwanted radiation (or light) can be controlled by shading or reflection. Shading can be achieved in several ways: paints, external shade cloths, nets (of various colours), partially reflective shade screens (Plate 6), water film over the roof and liquid foams between the greenhouse walls. Shading is the last resort for cooling greenhouses, because it affects productivity; however, shading can in some cases result in improved quality. A method widely

Ventilation – GAP recommendations

- For a coastal area like Magnesia, Greece, where during the critical summer period, outside solar radiation exceeds 900 W m^{-2} , a ventilation rate of about $0.06 \text{ m}^3 \text{ s}^{-1} \text{ m}^{-2}$ (corresponding, for a greenhouse with a mean height of 3 m, to an air exchange of 60 h^{-1}) is needed to maintain a ΔT of about $4 \text{ }^\circ\text{C}$. Natural ventilation allows for an air exchange rate of about 40 h^{-1} , above which, forced ventilation is necessary.
- For maximum efficiency, ventilators should, if possible, be located at the ridge, on the sidewalls and the gable.
- Total ventilator area equivalent to 15–30 percent of floor area is recommended; above 30 percent, the effect on the temperature difference is very small.
- If the external wind speed is not too low, natural ventilation can be more appropriate, creating a more humid and cooler (albeit less homogeneous) environment around the canopy.
- With roof ventilators, the highest ventilation rates per unit ventilator area are obtained when flap ventilators face the wind (100%), followed by flap ventilators facing away from the wind (67%); the lowest rates are obtained with rolling ventilators (28%).
- Systems such as exhaust fan and blower can supply high air exchange rates whenever needed. These simple and robust systems significantly increase the air transfer rate from the greenhouse, maintaining the inside temperature at a level slightly higher than the outside temperature by increasing the number of air changes.
- Forced ventilation by fans is the most effective way to ventilate a greenhouse, but electricity consumption is high. The estimated electrical energy requirements for ventilation of a greenhouse located in the Mediterranean are about 70 000 kWh per greenhouse ha.
- Ventilation fans should develop a capacity of about 30 Pa static pressure (3 mm on a water gauge), they should be located on the lee side or the lee end of the greenhouse, and the distance between two fans should not exceed 8–10 m. Furthermore, an inlet opening on the opposite side of a fan should be at least 1.25 times the fan area. The velocity of the incoming air must not be too high in the plant area; air speed should not exceed 0.5 m s^{-1} . The openings must close automatically when the fans are not in operation.
- With fan cooling alone (no evaporative cooling), little advantage can be derived from increasing airflow rates beyond 0.05 m s^{-1} .

adopted by growers because of its low cost is white painting, or whitening, of the cover material. The use of screens has been progressively accepted by growers and the last decade has seen an increase in the area of field crops cultivated under screenhouses (Cohen *et al.*, 2005). Roof whitening, given its low cost, is common practice in the Mediterranean Basin.

Baille *et al.* (2001) reported that whitening on glass material enhanced slightly the PAR (photosynthetically active radiation) proportion of the incoming solar irradiance, thus reducing the solar infrared fraction entering the greenhouse – a potential advantage compared with other shading devices, especially in warm

countries with high radiation load during summer. Another advantage of whitening is that it does not affect ventilation, while internal shading nets negatively affect the performance of roof ventilation. Whitening also significantly increases the fraction of diffuse irradiance, which is known to enhance radiation-use efficiency.

Screens mounted inside the greenhouse also contribute to decreasing the inside wind speed, thus lessening the leaf boundary layer and restraining the availability of CO₂ near the leaf surface. It is not clear whether shading nets are best used throughout the growth cycle or only during the most sensitive stages when the crops have a low leaf area and the canopy transpiration rate cannot significantly contribute to the greenhouse cooling (Seginer, 1994).

Evaporative cooling

One of the most efficient solutions for alleviating climatic conditions is to use evaporative cooling systems, based on the conversion of sensible heat into latent heat through evaporation of water supplied directly into the greenhouse atmosphere (mist or fog system, sprinklers) or via evaporative pads (wet pads). Evaporative cooling allows simultaneous lowering of temperature and vapour pressure deficit, and its efficiency is higher in dry environments. The advantage of mist and fog systems over wet pad systems is the uniformity of conditions throughout the greenhouse, eliminating the need for forced ventilation and airtight enclosure. Before installing a system, the air- and waterflow rates required must be calculated.

Fog system

Water is sprayed as small droplets (in the fog range, 2–60 nm in diameter) with high pressure into the air above the plants in order to increase the water surface in contact with the air (Plate 7). Freefall velocity of these droplets is slow and the air streams inside the greenhouse easily carry the drops. This can result in high efficiency of water evaporation combined with keeping the foliage dry. Fogging is also used to create high relative humidity, along with cooling inside the greenhouse. A wide range for fog system cooling efficiency ($n_{f,cool}$) is reported



Plate 7

Fog system used for greenhouse cooling

in the literature. According to Arbel *et al.* (2003), increased efficiency in the cooling process in relation to water consumption can be expected if fogging is combined with a reduced ventilation rate. Furthermore, a close relationship has been observed between $n_{f,cool}$ and system operation cycling (Abdel-Ghany and Kozai, 2006). Similar values for $n_{f,cool}$ have been reported by Li *et al.* (2006), who concluded that fog cooling efficiency increases with spray rate and decreases with ventilation rate.

Evaporative cooling – GAP recommendations 1: fog system

- Evaporative cooling allows simultaneous lowering of temperature and vapour pressure deficit and can lead to greenhouse air temperatures lower than the outside air temperature. Efficiency increases in dry environments.
- The advantage of mist and fog systems over wet pad systems is the uniformity of conditions throughout the greenhouse, eliminating the need for forced ventilation and airtight enclosure. Before installing a system, the air- and waterflow rates required must be calculated.
- Fog systems can be high (40 bars) or low (5 bars) pressure systems; high pressure systems are more effective than low pressure.
- The nozzles of the fog system should be located at the highest possible position inside the greenhouse to allow water evaporation before the water drops to the crop or the ground.
- During operation of the fog system, a vent opening of 20 percent of the maximum aperture should be maintained.
- Nozzles with fans provided 1.5 times better evaporation ratio and three times wider cooling area than nozzles without fans. Nozzles with fans produce a lower and more uniform air temperature.

Fan and pad cooling

The fan-and-pad cooling system (Plate 8) is most commonly used in horticulture. Air from outside is blown through pads with as large a surface as possible and which are kept permanently wet by sprinkling. The water from the pads evaporates and cools the air; outside air humidity must therefore be low. There are basically two systems of fan-and-pad cooling: the negative-pressure system and the positive-pressure system.

- The negative-pressure system consists of a pad on one side of the greenhouse and a fan on the other. The fans suck the air through the pad and through the greenhouse. The pressure inside the greenhouse is lower than the pressure outside; hot air and dust can therefore get into the greenhouse. There is a temperature gradient from pad to fan.



Plate 8

Pad (left) and fan (right) greenhouse cooling system

- The positive-pressure system consists of fans and pads on one side of the greenhouse and vents on the other. The fans blow the air through the pads into the greenhouse. The pressure inside the greenhouse is higher than outside; dust cannot get into the greenhouse.

In order to achieve optimal cooling, the greenhouse should be shaded. The waterflow rate, water distribution system, pump capacity, recirculation rate and output rate of the fan-and-pad cooling system must be carefully calculated and designed to provide a sufficient wetting of the pad and to avoid deposition of material.

The manufacturers' guidelines for pad selection and installation must be observed; furthermore, there are numerous considerations when designing a fan-and-pad cooling system. First, cooling efficiency should provide inside air humidity of about 85 percent at the outlet; higher air humidity slows down the transpiration rate of the plants. Plant temperature can then increase above air temperature. It is important that the pad material have a high surface, good wetting properties and high cooling efficiency. It should cause little pressure loss, and should be durable. The average thickness of the pad is 100–200 mm. It is essential that the pad be free of leaks through which air could pass without making contact with the pad. Different pad materials are available, such as wood, wool, swelling clay minerals, and specially impregnated cellulose paper.

The pad area depends on the airflow rate necessary for the cooling system and the permissible surface velocity over the pad. Average face velocities are 0.75–1.5 m s⁻¹. Excessive velocities may cause problems with drops entering the greenhouse. The pad area should be about 1 m² per 20–30 m² greenhouse area. The maximum fan-to-pad distance should be 30–40 m.

Pads may be positioned horizontally or vertically (more often the latter). Vertical pads are supplied with water from a perforated pipe along the top edge. In the case of horizontal pads, the water is sprayed over the upper surface. The water distribution must ensure even wetting of the pad. Pads have to be protected from direct sunlight to prevent localized drying out: salt and sand might clog them if they become dry. In areas with frequent sandstorms it is recommended to protect the wet pad with a thin dry pad serving as a sand filter. The pads have to be located and mounted in a way which permits easy maintenance and cleaning. They should be located on the side facing the prevailing wind.

Belt-driven or direct-driven propeller fans are used. Direct-driven fans are easier to maintain. Fans should be placed on the lee side of the greenhouse. If they are on the windward side, an increase of 10 percent in the ventilation rate will be needed. The distance between fans should not exceed 7.5–10 m, and fans should not discharge towards the pads of an adjacent greenhouse less than 15 m away. All

exhaust fans should be equipped with automatic shutters to prevent air exchange when fans are not operating, and also to prevent back-draught when some are not being used.

When starting the cooling system, the waterflow through the pad should be turned on first to prevent the pads from clogging. Fans should not be started before the whole pad has been completely wetted. When stopping the cooling system in the evening, the fan should be turned off before the waterflow through the pad. It is recommended to operate the cooling system by a simple control system depending on the inside temperature. The airflow rate depends on the solar radiation inside the greenhouse – that is, on the cladding material and shading – and on the evapotranspiration rate from the plants and soil. The airflow rate can be calculated by an energy balance. Generally, a basic airflow rate of 120–150 m³ per m² greenhouse area per hour will permit satisfactory operation of an evaporative cooling system.

Evaporative cooling – GAP recommendations 2: fan and pad

- The pad material should have a high surface, good wetting properties and high cooling efficiency. Suggested pad thickness is 200 mm. It is very important that there are no leaks where air can pass through without making contact with the pad.
- The pad area depends on the airflow rate necessary for the cooling system and the permissible surface velocity over the pad. Average face velocities are 0.75–1.5 m s⁻¹. The pad area should be about 1 m² per 20–30 m² greenhouse area. The maximum fan-to-pad distance should be 40 m.
- Fans should be placed on the lee side of the greenhouse. If they are on the windward side, an increase of 10 percent in the ventilation rate is necessary. The distance between fans should not exceed 7.5–10 m, and fans should not discharge towards the pads of an adjacent greenhouse less than 15 m away.
- When starting the cooling system, the waterflow through the pad should be turned on first to prevent the pads from clogging. When stopping the cooling system in the evening, the fan should be turned off before the waterflow through the pad.
- A basic airflow rate of 120–150 m³ per m² greenhouse area per hour will permit satisfactory operation of an evaporative cooling system.

Heating

Greenhouse heating is essential even in countries with a temperate climate, like the Mediterranean region, in order to maximize crop production in terms of quantity and quality and thus to increase overall efficiency. Heating costs are not only directly connected to profitability, but in the long term they may determine the survival of the greenhouse industry. In addition to the costs of high energy consumption, heating is associated with environmental problems through the emission of noxious gases.

Heating needs

There are various ways to calculate greenhouse heating needs (H_g) (W). The simplest is proposed by ASAE (2000):

$$H_g = U A (T_i - T_o) \quad \text{Eq. 2}$$

where:

U = heat loss coefficient ($\text{W m}^{-2} \text{K}^{-1}$) (see Table 1)

A = exposed greenhouse surface area (m^2)

T_i = inside air temperature (K)

T_o = outside air temperature (K)

Note that the estimation of greenhouse needs using Equation 2 did not take into account heat loss due to leakage. However it is a simple formula which can be used in order to estimate heating needs according to the greenhouse covering area and the desired temperature difference between inside and outside air.

TABLE 1
Total heat loss coefficient U at wind speed of n m/s

Covering materials	U value $\text{W/m}^2/\text{K}$
Single glass	6.0–8.8
Double glass, 9 mm air space	4.2–5.2
Double acrylic 16 mm	4.2–5.0
Single plastic	6.0–8.0
Double plastic	4.2–6.0
Single glass plus energy screen of	
- single film, non-woven	4.1–4.8
- aluminized single film	3.4–3.9

ASAE, 2000

Calculation of greenhouse heating needs

1. Measure the first three dimensions of the greenhouse:
 - Measure the length, width and height of the structure (to where the roof begins).
2. Measure the ridge of the greenhouse:
 - Measure the distance between the ground and the tip of the greenhouse's roof.
3. Measure the slope of the greenhouse roof:
 - The slope is the distance from the tip of the roof to the bottom of the roof.
4. Determine the surface area of the greenhouse's roof slope and two walls:
 - Use the formula: $2 \times (H + S) \times L$
where H = height, S = roof slope and L = length.
5. Determine the surface area of the remaining two walls:
 - Use the formula: $(R + H) \times W$
where R = ridge, H = height and W = width.
6. Determine the total surface area of the greenhouse:
 - Add together the results from step 4 and step 5.
7. Calculate the desired temperature difference:
 - Determine the best temperature for the interior of the greenhouse.
 - Determine the average coldest temperature for the area surrounding the greenhouse.
 - Determine the difference between the two temperatures.
8. Estimate the overall heat loss coefficient:
 - According to the covering material, refer to Table 1.
9. Estimate the heating needs of the greenhouse:
 - Multiply the total surface area of the greenhouse (step 6) by the temperature difference (step 7) by the overall heat loss coefficient (step 8).

Heating systems

The heating system must provide heat to the greenhouse at the same rate at which it is lost. There are several popular types of heating systems for greenhouses. The most common and least expensive is the unit heater system.

Unit heaters

Warm air is blown from unit heaters with self-contained fireboxes. Heaters are located throughout the greenhouse, each heating a floor area of 180–500 m². The typical cost, including installation is €4–8/m² of greenhouse floor.

Central heating

Steam or hot water is produced, plus a radiating mechanism in the greenhouse to dissipate the heat (Plate 9). The typical cost of a central boiler system for 1 ha, including heat distribution and installation, is €30–80/m² of greenhouse floor space, depending on the number of heat zones and the exact heat requirement.

**Plate 9**

Central boiler (left) and heating pipes for dissipating the produced heat (right)

Unlike unit heater systems, a portion of the heat from central boiler systems is delivered to the root and crown zone of the crop, resulting in improved growth and to a higher level of disease control. Placement of heating pipes is very important as it is directly related to heat loss; for example, the placement of pipes in the walls resulted in high losses through the sides.

**Plate 10**

Wall pipes

Wall pipe coils. Perimeter-wall heating can provide part of the additional heat requirement and contribute to a uniform thermal environment in the greenhouse. Both bare and finned pipe applications are common. Side pipes should have a few centimetres of clearance on all sides to permit the establishment of air currents and should be located low enough to prevent the blockage of light entering through the sidewall.

Overhead pipe coils. An overhead coil of pipes across the entire greenhouse results in heat loss through the roof and gables. The overhead coil is not the most desirable source of heat, as it is located above the plants; nevertheless, overhead heating systems can provide the additional heat required for winter months. They can also be used to reduce the risk of *Botrytis cinerea* outbreak, a major concern for many greenhouse growers

In-bed pipe coils. When the greenhouse layout allows it, the in-bed coil is preferable. By placing the heating pipes near the base of the plants, the roots and crown of the plants receive more heat than in the overhead system. Air movement caused by the warmer underbench pipe reduces the humidity around the plant. Heat is also kept lower in the greenhouse resulting in better energy efficiency. Such systems are suitable for plants grown on benches, fixed tables, and rolling or transportable tables.

Floor pipe coil. Floor heating is more effective than in-bed pipe coil heating. In addition to the advantages of in-bed coils, floor heating has the ability to dry the floor quickly. This is essential when flood floors are used for irrigation/fertilization. In this system, plants are set on the floor, which makes drying the floor difficult. Air movement caused by the warmer floor reduces the humidity around the plant. Such systems are suitable for plants directly grown on the floor, flooded-floor areas or work areas.



Plate 11
Pipe/rail heating systems

Pipe/rail heating systems

These systems maintain uniform temperatures with a positive effect on the microclimate. Air movement caused by the warmer pipe/rail reduces humidity around the plant. Such systems are suitable for vegetable production (Plate 11).

Radiant heater systems

These heaters emit infrared radiation, which travels in a straight path at the speed of light. The air through which the radiation travels is not heated. After objects such as plants, walks and benches have been heated, they will warm the air surrounding them. Air temperatures in infrared-radiant-heated greenhouses can be 3–6 °C cooler than in conventionally heated greenhouses with equivalent plant growth. Grower reports on fuel savings suggest a 30–50 percent fuel reduction with the use of low energy infrared-radiant heaters, as compared with the unit heater system.

Thermostats and controls

Various thermostat and environmental controllers are available for commercial greenhouse production. Sensing devices should be placed at plant level in the greenhouse: thermostats at eye level are easy to read but do not provide the necessary input for optimum environmental control. An appropriate number of sensors are needed throughout the production area. Environmental conditions can vary significantly within a small distance. Thermostats should not be placed in the direct rays of the sun as this would result in poor readings; they should be mounted facing north or in a protected location. It may be necessary to use a small fan to pull air over the thermostat to get appropriate values.

Energy heaters and generators

The risks associated with electrical power are always present. Heaters and boilers depend on electricity, and if a power failure occurs during a cold period, such as a heavy snow or ice storm, crop loss due to freezing is likely. A standby electrical

generator is essential for any greenhouse operation. Although it may never actually be used, even if it is needed for just one critical cold night, it becomes a highly profitable investment. A minimum of 1 kW of generator capacity is required per 200 m² of greenhouse floor area.

Heating for antifrost protection

Heating can be used to protect crops from freezing. It can also keep the greenhouse air temperature at levels above critical thresholds for condensation control. When not equipped with heavy and complicated heating systems, a unit heater is usually enough. Listed below are other useful recommendations for heating a greenhouse in order to avoid fruit freezing:

- Back the north wall to an existing structure such as a house or outbuilding for additional wind protection and insulation.
- Use water to store heat (a simple passive solar heating system): barrels or plastic tubes filled with water inside the greenhouse capture the sun's heat, which is then released at night when temperatures drop.
- Insulate the greenhouse; insulate plastic greenhouses with a foam sheet – easily placed over the structure at night and removed during the day; install an additional layer of plastic to the interior of the greenhouse for added insulation.

Heating checklist – Structure

- Covering
 - Replace damaged or excessively darkened panels
 - Repair or seal cracks or holes
 - Remove unnecessary shading compound to allow light penetration
- Vent system
 - Repair or adjust vents to reduce cracks at mating surfaces
- Thermal blankets
 - Operate through a complete cycle
 - Check that all seals close properly
 - Repair all holes and tears

Heating checklist (cont.) – Heating system

- Unit heater (forced air)
 - Check and clean burner nozzles
 - Ensure that adequate outside air is available to burners
 - Check flues for proper size and obstructions
 - Check fuel lines for leaks
 - Check heat exchangers for cracks and carbon and dirt buildup
- Boilers (steam or hot water)
 - Check and ensure that safety or relief valves are operative and not leaking
 - Clean tubes – both fireside and waterside
 - Clean blower fan blades
 - Maintain accurate water treatment records
 - Check boiler operating pressure and adjust to proper pressure
 - Insulate hot water heater or boiler
 - Make sure wiring is in good condition
 - Make sure good quality water is available for the system
- Steam or hot water delivery and return system
 - Fix pipe leaks
 - Be sure that there is enough pipe to transfer the available heat to maintain desired greenhouse temperatures
 - Clean heating pipes as needed, clean both inside and out, and clean heating fins
 - Adjust valve seats and replace if needed
 - Check for the proper layout of piping for maximum efficiency
- Control
 - Ensure that heating and cooling cycles or stages do not overlap
 - Check for accuracy of thermostats with a thermometer
 - Calibrate, adjust or replace thermostats
 - Make sure that thermostats are located near to or at plant level and not exposed to nearby heat sources
- Stand-by generator
 - Clean and check battery
 - Drain and refill generator fuel tanks
 - Check fuel tank and lines for leaks
 - Start and run weekly

Heating – GAP recommendations

- Keep a backup heating plan in case heater fails.
- Do not over seal the greenhouse in winter: bad ventilation leads to humidity problems.
- Have a weather station that serves as a greenhouse internal temperature monitor.
- Buy and use a thermostat to maintain the constant minimum temperature in your greenhouse.
- Use greenhouse fans to circulate the heat from greenhouse ceiling to floor.
- Install an alarm system for fire, smoke and CO₂ buildup.
- Replace greenhouses after 15–20 years (depending on the type of structure, materials used and climate control equipment).

CO₂ enrichment

The lack of climate control in many greenhouses in Mediterranean countries results in an inadequate microclimate that negatively affects yield components and input-use efficiency. CO₂ enrichment is essential to increase quality of produce; indeed, continuous or periodical increase of CO₂ inside the greenhouse may lead to an increase of over 20 percent in fruit production for both dry and fresh matter (Shanchez-Guerrero *et al.*, 2005). Better control of the greenhouse aerial environment can improve marketable yield and quality, and extend the growing season (Baille, 1999). Inside an unenriched greenhouse, the CO₂ concentration drops below the atmospheric level whenever the CO₂ consumption rate by photosynthesis is greater than the supply rate through the greenhouse vents. The poor efficiency of ventilation systems in low-cost greenhouses in Mediterranean countries, coupled with the use of insect-proof nets (Muñoz *et al.*, 1999), explains the relatively high CO₂ depletion (about 20% or more) reported in southern Spain (Lorenzo *et al.*, 1990). Possible solutions are:

- increase the ventilation rate through forced air;
- improve design and management of the ventilation system; or
- provide CO₂ enrichment.

The latter is widely adopted in the greenhouse industry in northern Europe to enhance crop photosynthesis under the low radiation conditions that prevail during winter. Enrichment reportedly increases crop yield and quality under a CO₂ concentration of 700–900 $\mu\text{mol mol}^{-1}$ (Nederhoff, 1994).

An important constraint is the short time period available for the efficient use of CO₂ enrichment, due to the need to ventilate for temperature control (Enoch, 1984). The fact that greenhouses have to be ventilated during a large part of the day makes it uneconomical to maintain a high CO₂ concentration during the day.

However, some authors advise supplying CO₂ even when ventilation is operating (Nederhoff, 1994) in order to maintain the same CO₂ concentration both in the greenhouse and outside, enriching to levels of about 700–800 μmol mol⁻¹ when the greenhouse is kept closed (usually in the early morning and the late afternoon).

In the absence of artificial supplies of carbon dioxide in the greenhouse environment, the CO₂ absorbed during photosynthesis must ultimately come from the external environment through the ventilation openings. The concentration of CO₂ within the greenhouse must be lower than that outside in order to obtain inward flow. Since potential assimilation is heavily dependent on carbon dioxide concentration, assimilation is reduced, whatever the light level or crop status. The ventilation of the greenhouse implies a trade-off between ensuring inflow of CO₂ and maintaining an adequate temperature within the greenhouse, particularly during sunny days.

Stanghellini *et al.* (2008) applied a simple model for estimating potential production loss, using data obtained in commercial greenhouses in Almería, Spain, and Sicily, Italy. They analysed the cost, potential benefits and consequences of bringing more CO₂ into the greenhouse: either through increased ventilation, at the cost of lowering temperature, or through artificial supply. They found that while the reduction in production caused by depletion is comparable to the reduction resulting from lower temperatures caused by ventilation to avoid depletion, compensating the effect of depletion is much cheaper than making up the loss by heating.

Optimal CO₂ enrichment depends on the margin between the increase in crop value and the cost of providing the CO₂. Attempting to establish the optimal concentration by experiment is not feasible because the economic value of enrichment is not constant but varies with solar radiation through photosynthesis rate, and with greenhouse ventilation rate through loss of CO₂ (Bailey and Chalabi, 1994). The optimal CO₂ setpoint depends on several influences: the effect of CO₂ on the photosynthetic assimilation rate, the partitioning to fruit and to vegetative structure, the distribution of photosynthate in subsequent harvests, and the price of fruit at those harvests, in addition to the amount of CO₂ used, greenhouse ventilation rate and the price of CO₂.

The principal source of CO₂ enrichment in the greenhouse used to be pure gas; nowadays more frequent use is made of the combustion gases from a hydrocarbon fuel, for example, low sulphur paraffin, propane, butane or natural gas and more recently also from biogas. In these cases, attention should be given to monitoring the SO₂, SO₃ and NO_x levels, which can damage the crops even at very low concentrations.

Dehumidification

Condensation refers to the formation of drops of water from water vapour. Condensation occurs when warm, moist air in a greenhouse comes into contact with a cold surface such as glass, fibreglass, plastic or structural members. The air in contact with the cold surface is cooled to the surface temperature. If the surface temperature is below the dew point temperature of the air, the vapour in the air will condense onto the surface. Condensation is heaviest in greenhouses from sunset to several hours after sunrise. During daylight hours, there is sufficient heating from solar radiation to minimize or prevent condensation, except on very cold, cloudy days. Greenhouses are most likely to experience heavy condensation at sunrise or shortly before. Condensation is a symptom of high humidity and can cause significant problems (e.g. germination of fungal pathogen spores, including *Botrytis* and powdery mildew.) Condensation can be a major problem – at certain times of the year, impossible to avoid entirely.

How to dehumidify the greenhouse

Combined use of heating and ventilation

A common dehumidification practice is simply to open the windows, allowing moist greenhouse air to be replaced by relatively dry outside air. This method does not consume any energy when excess heat is available in the greenhouse and ventilation is needed to reduce the greenhouse temperature. However, when the ventilation required to reduce the temperature is less than that needed to remove moisture from the air, dehumidification consumes energy. Warm greenhouse air is replaced by cold dry outside air, lowering the temperature in the greenhouse.

Absorption using hygroscopic material

There has been little research on the application of hygroscopic dehumidification in greenhouses, because installation is complex and the use of chemicals is not favourable. During the process, moist greenhouse air comes into contact with the hygroscopic material, releasing the latent heat of vaporization as water vapour is absorbed. The hygroscopic material has to be regenerated at a higher temperature level. A maximum of 90 percent of the energy supplied to the material for regeneration can be returned to the greenhouse air with a sophisticated system involving several heat exchange processes including condensation of the vapour produced in the regeneration process.

Condensation on cold surfaces

Wet humid air is forced to a cold surface located inside the greenhouse and different from the covering material. Condensation occurs on the cold surface, the water is collected and can be reused, and the absolute humidity of the wet greenhouse air is reduced. One metre of finned pipe used at a temperature of 5 °C can remove 54 g of vapour per hour from air at a temperature of 20 °C and with 80 percent relative humidity.

Forced ventilation usually with combined use of a heat exchanger

Mechanical ventilation is applied to exchange dry outside air with moist greenhouse air, exchanging heat between the two airflows. Based on the results of Campen *et al.* (2003), a ventilator capacity of $0.01 \text{ m}^3 \text{ s}^{-1}$ is sufficient for all crops. The energy needed to operate the ventilators is not considered; an experimental study (Speetjens, 2001) showed the energy consumption by the ventilators to be less than 1 percent of the energy saved.

Anti-drop covering materials

The use of anti-drop covering materials is an alternative technology for greenhouse dehumidification. “Anti-dripping” films contain special additives which eliminate droplets and form instead a continuous thin layer of water running down the sides. The search for anti-drip cover materials has been mainly focused on the optical properties of the cover materials.

When should dehumidification take place?

- Dusk: Reduce humidity to 70–80% as night falls to prevent condensation.
- Dawn: Reduce humidity to prevent condensation, and jumpstart transpiration as the sun rises.

Dehumidification – GAP recommendations

- Remove any excess sources of water in the greenhouse.
- Open the windows or the door to the greenhouse and allow excess moisture to escape ventilation.
- Turn on the greenhouse fan to improve air circulation.
- Purchase a humidity controller or a dehumidifier for use in the greenhouse.
- Use thermal screens at night to prevent radiative heat loss from plant surfaces.
- Place radiant heat sources near the crop to keep plant surfaces slightly warmer than air.

RATIONAL USE OF ENERGY AND RENEWABLE ENERGY SOURCES

Rational energy use is fundamental since energy accounts for a substantial proportion of total production costs. For northwest European conditions with heated greenhouses, annual energy consumption for conditioning is high (1 900 MJ m⁻² in Scandinavia). In Mediterranean areas, less energy is used (500–1 600 MJ m⁻²), but heating is increasingly adopted to achieve early production and a constant quantitative-qualitative yield, leading to higher energy use. Improved environmental control (e.g. more CO₂ supply, additional lighting), intensified production schemes and use of cooling systems all increase energy consumption. Average energy use accounts for 10–30 percent of total production costs, depending on the region.

Increase in production per unit of energy (energy efficiency) can be achieved through reduction of energy use and/or improvement of production. The major challenge in greenhouse operation is to find ways to contribute to improved energy efficiency combined with an absolute reduction of the overall energy consumption. The emission of CO₂ depends on the total use and type of fossil fuel. For example, when coal is used, CO₂ emission is 80–100 kg/MJ; for diesel, 75 kg/MJ; for propane, 65 kg/MJ; while for natural gas it is about 58 kg/MJ.

In general, the Mediterranean and north European regions have similar objectives with respect to optimizing production efficiency:

- autumn/winter – maximize the radiation quantity and minimize the energy loss;
- spring/summer – reduce high temperatures.

For rational use of energy (or fossil fuels) and reduction of greenhouse energy consumption, greater investment is required in order to achieve:

- efficient use of energy (i.e. amount of product per input of energy);
- reduction of energy requirement; and
- replacement of fossil fuels by more sustainable sources.

Energy-efficient climate control

Rational use of energy largely depends on energy-efficient greenhouse environmental control, which requires knowledge of the physiological processes (photosynthesis and transpiration, crop growth and development) in relation to the various environmental factors (temperature, light, humidity and carbon dioxide). However, to achieve the maximum benefits of energy-efficient environmental control, it is essential that the greenhouse itself and the control equipment (heating and ventilation system, CO₂ supply, lighting) are properly designed and frequently checked (at least at the start and once during the growth season). For example, optimized designs of pipe heating systems may prevent uneven temperature distribution and subsequent loss of energy and crop production.

Temperature control

Wind-dependent heating

One way to substantially reduce energy use is to lower heating temperatures: a 1 °C reduction gives an energy saving of around 10 percent. However, lowering temperature slows down growth and development of most crops and may significantly reduce quality. Thus a lower heating temperature will save energy, but is generally not economically feasible as it results in reduced crop production which is not usually compensated for by the lower energy costs. A more economic application of reduced heating temperatures is wind-dependent temperature control. Heat losses increase linearly as wind speed increases, therefore, energy can be saved by reducing the heating setpoints when it is windy and compensating for this using increased temperatures at low wind speeds. This method results in energy savings of 5–10 percent.

Temperature integration

Another option for energy-efficient temperature control is the so-called temperature integration (TI) method. This method is based on the fact that the effect of temperature on crop growth and production depends on the 24-hour average temperature rather than distinct day/night temperatures (de Koning, 1988). However, there are limits to this approach and plants have to be grown within the sub- and supra-optimal temperatures (e.g. tomato: > 15 °C and < 30 °C, and chrysanthemum: > 14 °C and < 24 °C) to prevent reduced quality and/or production levels due to poor fruit or flower development.

In southern regions in particular, the TI strategy can be implemented using higher than normal ventilation temperatures to maximize heating due to solar gain and to compensate these temperatures by running lower temperatures at night or on dull days.

In general, application of TI leads to higher temperatures during daytime and lower temperatures at night. However, the approach of using higher ventilation setpoints can also be combined with the use of lower day heating setpoints and higher temperatures under thermal screens at night. The aim is to fully exploit solar gain and, when additional heat is required, to add it preferably at night when heat losses are limited due to the closed thermal screen. There are potential energy savings of up to 20 percent; Rijdsdijk and Vogelesang (2000) demonstrated an 18 percent energy saving in pot plants, rose and sweet pepper with a band width of 8 °C. However, when setting band widths for temperature integration, a balance must be found between maximizing energy savings and minimizing detrimental effects on yield or quality. The balance varies enormously depending on the crop, so specific crop knowledge is required.

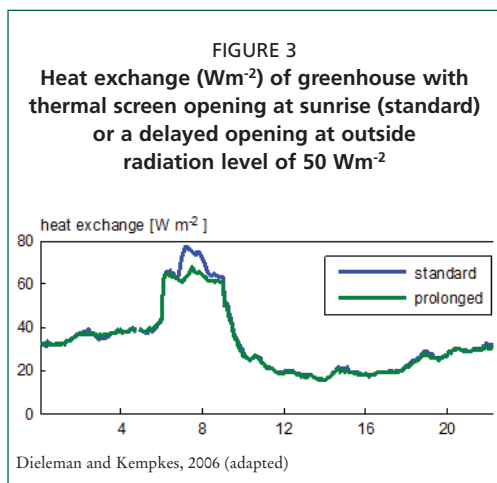
Humidity control

On a year round basis, a major fraction of the energy transfer from the greenhouse to the environment is by natural ventilation. Under relatively low radiation and moderate ambient temperatures, natural or forced ventilation is generally used to prevent high humidity. Consequently a substantial fraction (5–20%) of the total energy consumption is related to humidity control. Although high humidity is generally associated with increased risk of fungal diseases and reduced quality (e.g. *Botrytis*, blossom end rot), it may also be positive for crop production and quality (Montero, 2006). Reducing the level of humidity of the air is costly as a result of the energy required and should be assessed against the added value of the crop. An increase in the humidity setpoint of 5 percent decreases the energy consumption by approximately 6 percent. To reduce “humidity control related” energy consumption, there are several options:

- higher humidity setpoints
- reduction of the transpiration level of the crop
- active dehumidification with heat recovery

Thermal screens

Energy-efficient thermal screen control involves achieving a balance between the production and quality effects related to humidity and light, and energy saving. Energy-efficient (humidity) screen control can be achieved by opening the screen prior to the ventilators to maintain a given humidity setpoint. By closing the screen at night, an additional energy saving (4%) can be obtained without any production losses if the opening of the screen is delayed until radiation levels are outside $50\text{--}150\text{ Wm}^{-2}$; the heat exchange of the greenhouse is thereby reduced for a longer period during the early morning hours (Figure 3).



Reduction of transpiration

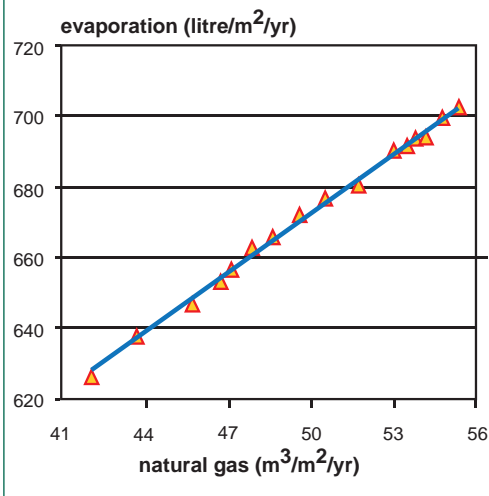
Reduction of transpiration may have positive effects on energy efficiency since lower transpiring crops bring less water into the air and therefore require less energy for humidity control under low irradiation conditions (Figure 4). Higher CO_2 levels, by decreasing stomatal conductance and thus transpiration, may also improve energy efficiency by 5–10 percent without affecting photosynthesis or growth. Controlled reduction of the leaf area for crops with a high leaf area index, such as pepper, may reduce energy use without any impact on production. Halving the leaf area by

removing old leaves in tomatoes resulted in a 30 percent reduction in transpiration with no detrimental effect on crop yields (Adams *et al.*, 2002).

Crop-based environmental control

Operational control should not aim at individual environmental factors (temperature, humidity, CO₂) but at energy-efficient crop production and quality control, taking into account the impact of control actions on both crop production and energy consumption. While this (model-based) approach has been under research since the early 1980s, its practical application in on-line control of greenhouses remains limited because it requires the end-user to adopt an entirely new approach and abandon current practices.

FIGURE 4
Relation between yearly evaporation and energy use for a traditionally grown tomato crop under northwestern European conditions



Climate control – GAP recommendations

- Carry out regular maintenance; check and calibrate devices, sensors, pumps, valves, ventilators etc. no less than at the start of each cropping period.
- Do not place thermostats/sensors in direct sunlight; use aspirated sensors.
- Optimize incoming solar energy in cold conditions by delaying ventilation or opening of thermal screens.
- Use greater differences between day and night temperature settings for ventilation (4–6 °C); adopt automatic temperature integration if available.
- Monitor settings of environmental control system or thermostats; check regularly that they are in line with the production strategy.
- Consider use of higher humidity setpoints during periods with lower irradiation in heated greenhouses.
- When using a thermal screen, first open the screen (rather than the vents) to reduce humidity.
- When available, apply CO₂ at least to ambient concentration (i.e. 340–370 μmol mol⁻¹); it does not reduce energy use but significantly contributes to crop growth and production.

Rational energy use in practice

While the introduction of new innovative environmental control technologies will increase energy efficiency, major advances can be made by improving the hardware design of heating and ventilation systems and increasing the accuracy and the frequency of controls of the sensor network. Thus, the major practical recommendations for rational energy use largely depend on the grower's operational control of the available hardware in terms of heating, ventilation and cooling systems, screens etc.

Energy saving: reduction of greenhouse energy requirement

Covering materials and screens

Most energy loss in natural ventilated greenhouses occurs through:

- convection and radiation from the greenhouse cover; and
- sensible and latent heat transfer through ventilation.

Improved insulation and reduced ventilation are therefore the first steps towards creating energy-conserving greenhouses. The basis of energy reduction is good maintenance of greenhouse hardware (doors, cover, sidewalls, foundation). Measures must be taken to prevent unnecessary air leakage from the greenhouse: keeping greenhouse doors closed, sealing air leakages, repair of broken cover material and sidewalls, and uniform closure of natural ventilators.

Increasing the insulation value of the greenhouse has a major impact on energy consumption as most energy loss takes place through the cover. Therefore different technologies can be applied, including increase of the insulation value using double or triple layer materials and application of coatings to reduce radiation loss. A combination of these techniques may lead to a significant reduction in energy use for the entire greenhouse system (Table 2).

However, a major disadvantage of most insulating covers is the reduction in light transmission and increased humidity. In practice, the potential energy saving of double and triple covering materials is rarely achieved, since the grower will try to compensate for the higher humidity levels by increasing the dehumidification of the greenhouse environment.

For energy conservative (film) greenhouses, materials combining high light transmission with low IR transmission are preferred (Hemming, 2005). PE and EVA films generally have high IR transmission

TABLE 2
Effects of different types of greenhouse covering materials on annual energy use of year-round tomato crop

Greenhouse cover	(Fossil) energy use (m ³ natural gas/m ²) ^a	
Single glass	53	(100%)
Single glass with screen	40	(75%)
Double cover	40	(75%)
Double with screen	33	(62%)
Double with low emission	28	(53%)
Three-layer with low emission	26	(49%)

^a 1 m³ natural gas equivalent to approx. 31.5 MJ.

Bot et al., 2005

rates which makes them less suitable when designing energy-efficient greenhouses (Table 3).

Screens

A thermal screen adds an additional barrier between the greenhouse and its surroundings and reduces both convection and ventilation loss. Screens can be either fixed or movable. Fixed screens are normally used during the early growth stage and production period of the crop, but the constant reduction of the light level and increased humidity limit the period of application and consequently the potential energy saving.

Movable screens have less impact on light transmission than fixed screens or double covering materials. Screens may reduce energy use by more than 35–40 percent, depending on the material (Table 4). In practice, movable screens are closed for only part of the entire 24-hour period depending on the grower's criteria for opening and closing, which are generally related to humidity and light levels. In commercial practice, this results in energy savings of about 20 percent in

TABLE 3
Visible light transmission (diffuse) and IR transmission of different greenhouse covers

Material	Thickness	Light transmission	IR transmission
"Standard" glass	4mm	82%	0
Hard glass	4mm	82%	0
Anti-reflection glass	4mm	ca.89%	0
PE film	200µm	ca.81%	40–60%
EVA film	180µm	ca.82%	20–40%
ETFE membrane	100µm	88%	15–20%
Polycarbonate (2-layer)	12mm	61%	0
PMMA (2-layer)	16mm	76%	0
Polycarbonate zigzag	25mm	80%	0

TABLE 4
Greenhouse screen materials and their characteristics

Type	Transmission in direct light	Transmission in diffuse light	Energy saving
ILS 10 Revolux	71	65	45
ILS 50 Revolux	44	40	20
ILS Clear	83	77	47
XLS 10 Revolux	87	80	47
XLS 15 Firebreak	50	47	25
XLS 16 Firebreak	39	37	20

northwest Europe. For southern regions the application of screens (and energy-saving covering material) may be less economically feasible. Due to the general lower energy use (see Figure 4) the financial benefits of savings will be less while investments remain relatively high.

Energy-efficient cooling

Ventilation

In almost all regions worldwide, and especially at southern latitudes, there is a large surplus of solar energy requiring efficient cooling systems to reduce the air temperature. Natural ventilation is the most common method of cooling, and optimizing the geometry of the greenhouse can enhance natural ventilation. With a roof slope of up to 30°, the ventilation rate significantly increases and traditional horizontal roof greenhouses are replaced with symmetrical or asymmetrical greenhouses. Windward ventilation is more efficient than leeward ventilation, so new greenhouse constructions have larger openings facing the prevailing winds.

Shading

Shading to reduce the solar energy flux into the greenhouse during periods with an excessive radiation level is a common way of achieving passive cooling. Mobile shading systems mounted inside or outside have a number of advantages, such as the improvement of temperature and humidity, quality (e.g. reduction of blossom end rot in tomato crops) and a clear increase in water-use efficiency. In southern regions in particular, movable and external shading are very efficient at improving energy efficiency.

Specific materials which absorb or reflect different wavelengths or contain interference or photo or thermochromic pigments may be used to bring down the heat load but mostly these materials also reduce the PAR level. Materials reflecting part of the sun's energy not necessary for plant growth (near-infrared, NIR) show promising results (e.g. Garcíá-Alonso *et al.*, 2006) and may be applied either as greenhouse cover or as screen material.

Mechanical cooling

Mechanical cooling (fans, heat pumps and heat exchangers) can maintain the same greenhouse temperature as does natural ventilation; it can further reduce the temperature, especially under high ambient temperatures or high radiation levels. With high cooling capacity it is possible to keep the greenhouse completely closed, even at maximum radiation levels. However, all practical and experimental experience shows that return on investment for these systems is poor for all regions in the world, except for direct evaporative cooling by fogging/misting and indirect evaporative cooling (pad and fan).

This is most likely the result of the positive effects of lower temperature and higher humidity resulting in better growth and production, at least with major

fruit and vegetables. Therefore, direct evaporative cooling by misting and pad and fan cooling still gives the best economic results and increases energy efficiency primarily through the impact on production.

Energy reduction in practice

The reduction of the energy requirement is related to the grower's strategic choices in relation to greenhouse construction, covering material and environmental equipment in terms of heating system, ventilation, cooling, screens etc. Increased investment is required and needs to be considered in terms of return on investments.

Energy efficiency – GAP recommendations

- Take care of regular maintenance of the greenhouse hardware (doors, cover, sidewalls, foundation, ventilators, pad/fan, screen material etc.).
- Keep doors closed, seal air leakages, replace broken cover material and ripped screens.
- Select greenhouse cover materials with low IR transmission.
- Use (moveable) thermal screens for areas with low average or low night temperatures.
- Use thermal screens in particular in locations characterized by clear sky to reduce radiative heat exchange with the sky canopy.
- Replace horizontal roof greenhouses with symmetrical or asymmetrical greenhouses with roof slopes up to 30°.
- When using natural ventilation, build greenhouses with large windward ventilation openings located in line with the prevailing wind direction.
- If cooling is required, use misting or pad and fan cooling; if not sufficient, add a shading screen.
- Replace old greenhouses with newer more energy-efficient models.

Replacement of fossil fuel by other sustainable sources

As CO₂ emission is directly related to the use of fossil fuels for heating and cooling greenhouses, alternatives (e.g. solar and geothermal energy, biomass and waste heat) can significantly help achieve the reduced CO₂ emission targets. Using waste heat and CO₂ supply from combined heat and power generators (CHP) and feeding the electricity to the national grid can save a significant fraction of fossil fuel. While energy is not directly saved at greenhouse level, CHP reduces CO₂ emission at national level by reducing the CO₂ emission of the central power plants.

However, the economically feasible application of CHP largely depends on the local situation. Sometimes it is not allowed or is not technically feasible to feed electricity into the national grid, or the price of electricity is (too) low. Stand-alone use of CHP (for electricity used at greenhouse farm level) is only an option

in large-scale greenhouses and requires solutions for the imbalance between the not-synchronized heat and power use at farm level, for example, using heat storage systems.

Biomass and anaerobic digestion are good alternatives for fossil fuel but the availability and massive quantities needed and uncertainty about the energy content are major drawbacks for large-scale application. For example, a 1-MW biomass source may require up to 2 500 tonnes of dry mass per year. This not only requires significant investments but also logistic solutions and the availability of this biomass in the surrounding area. Furthermore, the continuity of the biomass supply may be a problem as the storage of required amounts of gas is almost impossible. With regard to CO₂ from this gas, special attention should be paid to pollution aspects after burning components like SO₂/SO₃ and NO_x may seriously damage the crop. However, for small-scale application and stand-alone greenhouses without connection to energy infrastructure, it may be a valid option.

Depending on the geology of the area, geothermal energy (water temperatures > 60 °C) is a promising alternative. Large (volcanic) areas in the world (e.g. Turkey) have geothermal potential which can be economically feasible for greenhouse heating but so far the number of geothermal heated greenhouses is limited, primarily because of the high financial risks related to drilling the hot water well. In the Netherlands a geothermal source (water 65 °C, depth 1 700 m) for greenhouse heating required an investment of about € 5.5 million (price level 2007). The total costs, however, can differ greatly as in other areas of the world geothermal energy is available at lesser depths. For the economic application of deep geothermal energy, in general a large greenhouse area (> 20 ha) has to be connected to the source.

Sustainable energy resources – GAP recommendations

The use of alternative energy sources depends on the strategic and long-term choices of the grower and usually becomes relevant if previous steps have led to a reduction in the required energy input per unit of area. Although all previous recommendations also have to be considered from the point of view of economic feasibility, this last step requires specific attention to risk analysis concerning the reliability of availability/delivery of the alternative source and its price fluctuations since in general the investment costs related to this step are generally (very) high. For economic reasons (economy of scale), application of more sustainable energy sources generally requires connection to a large greenhouse area. It is therefore recommended to use specialized consultants and advisory services when considering the use of these sustainable energy sources.

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