Italian Journal of Agrometeorology
Rivista Italiana di Agrometeorologia

Firenze University Press
www.fupress.com/ijam

OPEN ACCESS

Citation: C. Kittas, W. Baudoin, E. Kitta, N. Katsoulas (2022) Sheltered horticulture adapted to different climate zones in Radhort Countries. *Italian Journal of Agrometeorology* (2): 3-16. doi: 10.36253/ijam-1655

Received: May 12, 2022

Accepted: June 4, 2022

Published: January 29, 2023

Data Availability Statement: All relevant data are within the paper and its Supporting Information files.

Competing Interests: The Author(s) declare(s) no conflict of interest.

Sheltered horticulture adapted to different climate zones in Radhort Countries

Constantinos Kittas[1,*], Wilfried Baudoin[2], Evangelini Kitta[1], Nikolaos Katsoulas[1]

[1] *University of Thessaly, Greece, University of Thessaly, Department of Vegetal Production and Rural Environment, Phytokou Street, 38444 Volos, Greece*
[2] *Former FAO Senior Officer , Plant Production and Protection Division Rome, Italy*
*Corresponding author. E-mail adress: ckittas@uth.gr

Abstract. Over the last decade, the total population of the sub-Saharan region of Africa has been increasing rapidly at a rate of more than 3% annually, with urbanization expected to be approximately 40% of the total population by 2050. Parallel growth has not been achieved in the agricultural sector in West Africa, with vegetable production and consumption being amongst the lowest in the world. This has aggravated the already food insecurity and malnutrition situation in the region. In this context, and within the framework of their agricultural development policies, 10 countries of West Africa (Burkina Faso; Cabo Verde; Côte d'Ivoire; Guinée; Guinée Bissau; Mali; Mauritanie; Niger; Sénégal; Chad), established the "African Network for Horticultural Development "RADHORT" (Réseau Africain pour le Développement de l'Horticulture), in order to cooperate for the diversification and intensification of horticulture in the region. The countries of RADHORT cover different climate zones ranging from the arid climate (desert), to the Sahelian zone (semi-arid), to the dry tropical zone (with long dry season and short rainy season), and to the wet tropical zone (humid zone with bimodal rainfall). Temperatures and global radiation are very suitable for vegetable production in tropical countries throughout the year, but open air cultivation can be severely hampered by high temperatures, winds, heavy rainfall, while being exposed to pest and disease infestation. Sheltered cultivation will help to moderate negative effects of climate factors on the crop, improve water productivity and the efficiency of eco-friendly pest and disease management. The paper analyses and discusses different technical options of sheltered cultivation to be tested in RADHORT countries, as a means to enhance horticulture crops productivity and quality for meeting the growing demand of an expanding rural and urban population.

Keywords: greenhouse, nethouse, protected cultivation, Tropics.

INTRODUCTION

The total population of the sub-Saharan region of Africa has been increasing rapidly at a rate of more than 3% annually during last decade, with an urbanization rate expected to be approximately 40% of the total population by 2050 (Saghir and Santoro, 2018). Parallel growth has not been achieved in the agricultural sector in West Africa, with vegetable production, availability and consumption being amongst the lowest in the world. This has compounded the already food insecure and malnutrition situation in the region.

In this context, the intensification and development of the horticulture sector has considerable potential for contributing to enhanced food and nutrition security at global level. It would be based on the sustainable use of available land and water resources and would generate employment and income, contributing significantly towards improving the livelihood particularly of small-scale farmers, women and youth. To this end, and within the framework of their agricultural development policies, 10 countries of West Africa, have joined together and committed themselves to the intensification and diversification of horticultural crops in the region. To this effect they established the African Network for Horticultural Development "RADHORT" (Réseau Africain pour le Développement de l'Horticulture)[1], as a framework to facilitate regional cooperation and integration. RADHORT is a major result of a project for the development of horticultural production in West Africa implemented since 1988 by FAO under the FAO-Belgium Cooperation Program (GCP/RAF/244/BEL). The member states of RADHORT are Burkina Faso, Cabo-Verde, Ivory Coast, Guinea, Guinea-Bissau, Mali, Mauritania, Niger, Senegal and Chad (FAO, 2016)[2]. The countries of RADHORT are located in the Tropics.

However, they cover different climate zones ranging from desert, semi-desert to subtropical and tropical.

The scope of RADHORT is the development of the horticultural sector with the aim of achieving intensification and development of horticulture production in support of improved food and nutrition security in the context of the rapidly increasing population of African countries and the rising urbanization rate.

Within the effort for the development of the horticultural sector in RADHORT countries, a description and an analysis are made in this article of different technical options for the rational design and equipment of sheltered cultivation based on the climatic features prevailing in the region covered by the RADHORT countries. These technical options could be a basis for applied research at regional level with the aim of promoting sheltered cultivation as part of an innovation toolbox in support of sustainable crop intensification in the West Africa region.

THE CLIMATE CHARACTERISTICS OF RADHORT COUNTRIES

The countries of RADHORT are located in the Tropics. However, looking at the map of Climate zones of Africa (Figure 1, http://www.synergy-energy.co/africa-climate-map.html), it is noted that, according to Köppen- Geiger climate classification (Köppen, 1936), the RADHORT countries (Burkina-Faso, Cabo Verde, Guinea, Guinea Bissau, Mali, Ivory coast, Mauritania, Niger, Chad and Senegal), cover different climate zones ranging from the arid climate (desert), to the Sahelian zone (semi-arid), to the dry tropical zone (tropical with long dry season and short rainy season), to the wet tropical zone (humid zone with bimodal rainfall).

This situation illustrates the fact that there is very large variation of climate features within the RADHORT countries.

WHY GREENHOUSES IN THE TROPICS?

The tropics are a belt of the earth surrounding the Equator. They are delimited in latitude by the Tropic of Cancer in the Northern Hemisphere at 23°26'13.1" (or 23.43696°) N and the Tropic of Capricorn in the Southern Hemisphere at 23°26'13.1" (or 23.43696°) S; these latitudes correspond to the axial tilt of the Earth.

In tropical regions, the temperatures and the global radiation are very suitable for vegetable production throughout the year. However, open field cultivation can be severely hampered by adverse weather conditions, including high temperatures, drying winds, high pest and disease incidence, as well as heavy rainfall and high relative humidity (von Zabeltitz, 2011).

The aim of promoting sheltered cultivation is to intensify the production of safe vegetables of better quality, allowing to reduce the applications of synthetic chemical pesticides and saving on water and land resources. Crop production under sheltered cultivation permits continuous crop production throughout the year with efficient use of inputs: water, fertilizers, labor, space and the implementation of biological control as part of integrated plant protection management (IPM). With respect to water, which is a serious limiting factor in several RADHORT countries, it was reported by Katsoulas et al. (2012), that crops grown in a nethouse consumed about 20-40% less water than in the open field. The same reduction occurs for crops in unheated simple (low tech) greenhouses, while for crops under sophisticated (high tech) greenhouses, water saving against open field can exceed 60% (Nederhoff and Stangellini, 2010).

[1] http://www.fao.org/agriculture/crops/thematic-sitemap/theme/hort-indust-crops/radhort/presentationgenerale/en/

[2] The constitutional act of RADHORT has been undersigned by the Ministers of agriculture of the ten founder countries and the acceptance instrument has been deposited at FAO for record and custody.

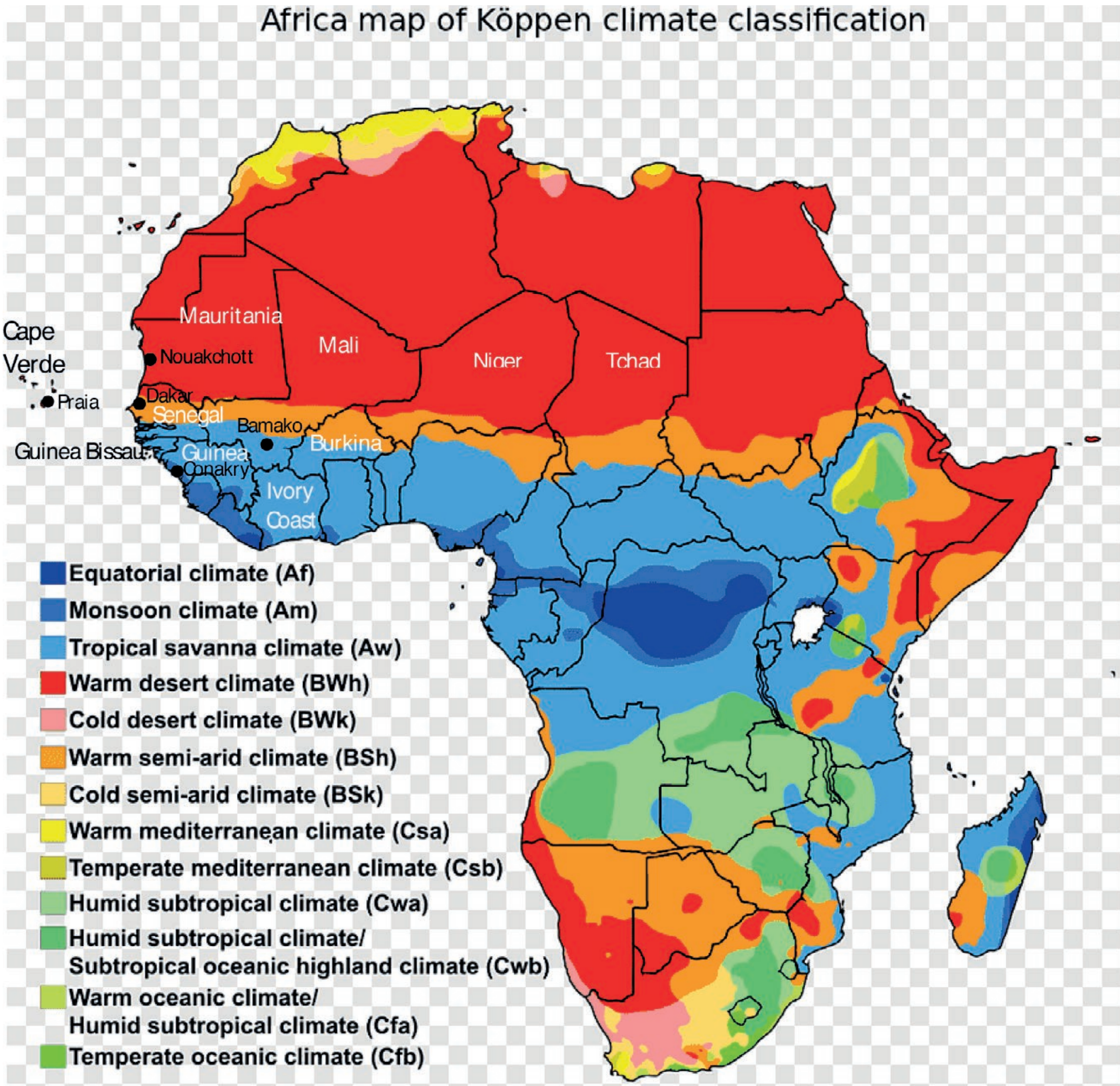

Fig. 1. Climatic Zones of Africa and RADHORT countries.

Sheltered cultivation can be defined as any agricultural activity taking place under a protective structure. A protective structure is defined as any structure designed to modify the environment under which plants are grown.

Protective structures are generally classified in two main groups:

Greenhouses, referring to structures covered (at least the roof) with non-porous materials and nethouses, which are covered with porous materials.

Greenhouses, besides the cover sheets, can be equipped with screen nets, which are used either for insect proofing or shading. Insect-proof nets can be applied on the openings of the greenhouses, while shading nets can be added on top of the greenhouse roofs to prevent overheating.

Nethouses offer a physical protection of the crop against adverse climate factors (e.g. wind, dust, etc) and insect pests while also offering a cooling effect by reducing the incoming solar radiation.

The development and use of efficient, cheap but cost-effective technologies for adapted protective-shelter structures is crucial for the expansion of protected cultivation in the tropics. This means that imported turnkey greenhouses from countries with subtropical or temperate climate can be avoided. Instead, the design of constructions, which are adjusted to local climate parameters and built with locally available materials, including *Bambusa vulgaris*, *Casuarina equisetifolia*, *Borassus flabellifer*, should be investigated and promoted for the different climate zones (FAO, 1999).

Vegetable production in tropical climates under adapted shelter structures with selected covering materials will result in higher yield of better quality, secured harvest all year round, less susceptibility to diseases, less insect damage, less physical damage and flooding by heavy rain-fall, reduced water consumption, more efficient use of fertilizers, less chemical pest and disease control and a more comfortable working environment. The increase in productivity and better quality produce obtained with fewer and cost-effective inputs are expected to lead to an increase of revenue for the farmers. In fact, a cost-benefit analysis conducted in Kenya (Nakuru, 0°18'11.1564''S, 36°4'48.0900''E, warm-summer Mediterranean climate – Csb) comparing the profitability of tomato cultivation in low tech unheated greenhouses and in the open field (Wachira et al., 2014), demonstrated that average yields in greenhouse were about 10 times higher than in the open field.. Net profits per square meter were 13 times higher for tomato cultivation in greenhouse than in the open field even though fixed costs, i.e. the sum of all costs that do not vary with the production, were on average more than 60 times higher for greenhouse farming. Furthermore, a cost benefit analysis in warm semi-arid region (Rohtak, India, 28°53'40.09"N 76°35'21.01"E, BSh) (Duhan, 2016) showed that growing vegetables under low cost unheated greenhouses is more than 10 times more profitable as compared to open field production.

GENERAL RULES FOR TECHNOLOGIES OF PROTECTED HORTICULTURE IN TROPICS

Some general rules and technologies suitable for the climatic conditions prevailing in the RADHORT countries are presented as guiding principles for the rational development of protected agriculture in such countries.

Design criteria for greenhouses are based on the climate conditions in situ and climate control needs in line with the analysis of the limiting factors for plant growth, the general greenhouse structure and covering materials requirements, taking into consideration local standards if existing, as well as locally available, suitable and cost effective materials.

Climate Conditions for assessing the Regional Suitability for Greenhouse Cropping

Greenhouses have to be designed in regard to the needs of the plants and conditions of the different climate zones. To check the suitability of a region for protected cultivation, the climate data should be compared with those of other regions and with the main requirements of the plants to be grown in the greenhouses.

For vegetables, the main climate requirements and set points for climate control for thermophile species are (Kittas, 1995; von Zabeltitz and Baudoin, 1999):

- T_{max}: mean monthly maximum temperatures below 32-34°C
- T_{min}: mean monthly minimum temperatures greater than 12°C
- SR: mean minimum outside solar radiation 7.5 MJ/m^2/day.
- HR: relative humidity in the range of 70 to 90%

From the analysis of climate data in RADHORT countries, it can be concluded that, there is no need for heating since T_{min}> 12°C always and this is the case for all RADHORT countries. To the contrary, in the Tropics, the greenhouse design and equipment has to face a specific problem of climate control, which is the avoidance of greenhouse overheating.

By using the climate data of each area a climograph can be elaborated to assess the local suitability for greenhouse cropping (Kittas, 1995). More precisely, the climograph for selected sites will be obtained by combining the average maximum monthly outside temperature and the corresponding average global radiation for a given region during the 12 months of the year. By adopting 27°C and 33°C as reference temperature set points, the following climate control requirements can be defined to ensure good plant growth:

- T_{max}< 27°C a good ventilation is sufficient
- 27°C <Tmax< 33°C ventilation + shading are needed
- T_{max}> 33°C cooling is needed.

The General Design Requirements

Based on the climate control requirements for good plant growth, the following general design criteria and technical specifications have been elaborated for greenhouse cultivation in the tropics (Baudoin and von Zabeltitz, 2002):

- Cladding material: Plastic film, with the following desirable characteristics:
  - Long lasting: Longevity should be for a minimum of 3 to 4 years even with high global radiation.

- Light diffusing: In order to increase homogeneity of the solar radiation but also to increase the shading effect of the cover.
- Easy to clean from prevailing dust.
- UV-Absorbent and if possible photo-selective against insects' infestation.
- Antifog to avoid condensations on the cover.
- Antidrip to avoid wetting the plants underneath.
- IR reflectant for heat reduction purposes.
- Covering film must not flutter in the wind, but has to be stretched and tightly fixed by simple stretching devices.

- Shade nets: They are usually white with Shading Intensity (S.I.), as required, between 20 and 40% and 2-3 years longevity.
- Ventilation: To be efficient, ventilation openings (ventilators) are needed at sidewalls and the ridge. Ridge ventilation is absolutely necessary, if mean maximum temperature is above 27°C. Efficient ventilation should aim at reducing the difference between inside and outside greenhouse temperature.
- Insect proofing: Ventilation openings have to be equipped with nets of 50 mesh against penetration of insects, without decreasing the ventilation efficiency for more than 30%. Therefore, the ventilation area must be adequately increased. The S.I. of insect proof nets is about 20%.
- Structural and geotechnical design: For the four prevailing climates (BSh, BWh, Aw, Am) the design has to favor the natural (passive) ventilation, which can be obtained by sidewall and ridge openings (equivalent to at least 30% of the floor area), both covered with insect-proof nets. In Aw and Am climates, it should be possible to close the vents in order to operate fan and pad evaporative cooling when needed (Franco et al., 2014). Gutter height: The gutter height should be about 2.5 to 3 m minimum. The higher the structure with ridge ventilation, the greater the ventilation efficiency by the chimney-effect. To the extent possible, the use of locally available and renewable construction materials is advisable to contain the investment cost. The greenhouse structure and foundation must be designed and calculated according to the "EN 1990 'Eurocode - Basis of structural and geotechnical design", against wind, pressure and suction forces, and crop loads.
- Rainwater collection: Gutters are necessary to not only drain off the rainwater but also for the collection and storage of rainwater, which can be recycled for irrigation and other purposes.
- Greenhouse irrigation: localized irrigation systems should be applied, to avoid increasing the air-humidity inside the greenhouse. It will help to control weed growth and contain the infestation of pests and diseases.

APPROPRIATE GREENHOUSE TYPES FOR RADHORT COUNTRIES

Climographs have been elaborated, using the meteorological data of Nouakchott (Mauritania), Dakar (Senegal), Praia (Cabo Verde), Conakry (Guinea)and Bamako (Mali) (Table 1), with a view to characterizing the suitability for selected greenhouse types in these sites, which could be extrapolated at regional level to iso-climate areas in the RADHORT countries. Ierapetra (35°00'42.70"N, 25°44'32.42"E) on the south coast of the island of Crete (south Greece), has been used as a reference location for comparison purposes. Ierapetra is the area with the highest concentration of protected crops in Greece with Mediterannean climate (dry summers and mild, wet winters), classified as Csa by the Köppen-Geiger system[3].

The analysis is based on the climograph of the following cities:

(1). Nouakchott, Mauritania (18°09'N 15°58'W, warm desert climate), classified as BWh in the Köppen-Geiger system vs. Ierapetra and Praia, Cabo Verde (14°55'N 23°31'W, warm desert climate, BWh) vs Ierapetra (Figure 2), with relatively lower maximum temperatures than the corresponding values in continental areas, due to the beneficial effect of sea breezes from the Atlantic.

(2). Dakar, Senegal (14°40'N 17°25'W, warm semi-arid climate, BSh) vs Ierapetra (Figure 3).

(3). Conakry, Guinea (9°31'N 13°42'W, monsoon climate, Am) and Bamako, Mali (12°39'N; 8°0'W, tropical savanna, Aw) vs Ierapetra (Figure 4).

a. Climograph of Nouakchott and Praia vs Ierapetra

The climate in Nouakchott is warm desert, it means hot and rather dry with very low rainfall over the year. From Figure 2, it can be suggested: (i) Greenhouse to be the highest possible for improving the chimney effect for higher ventilation rate; (ii) Ventilation needs to be very efficient throughout the year with openings up to 30-35% of the total floor area. The lateral and

[3] The major greenhouse types adapted to Ierapetra are: Tympaki type (similar to Parral), Tunnel and modified arched roof single layer polyethylene covered greenhouses equipped with vent openings for natural ventilation.

Table 1. Meteorological data of RADHORT countries and Ierapetra- Greece.

City, Country	Data	Units	1	2	3	4	5	6	7	8	9	10	11	12	Total
Ouagadougou Burkina Faso 12,37°N/1,53°W	Tmean	ºC	25,1	28	31,4	33,2	32,4	29,7	27,5	26.5	27.4	29.1	28.2	25.4	
	Tmean	ºC	25,1	28	31,4	33,2	32,4	29,7	27,5	22	21.8	25,1	28	31,4	
	Tmax	ºC	33	36	38	39	38	35	32	31	33	36	36	33	
	HR	%	22,8	20,3	21,8	35,7	49,80	62,5	72,5	79	75,3	58,2	35,4	26,8	
	SR	MJ/m²/d	19,7	22,9	23,2	23	22,3	22	20,6	19,3	20,8	21,3	20,7	19,1	
	Rainfall	mm	0.1	0.5	5.9	26.5	66.8	97.5	176	214	121	33.5	1.2	0.2	743.2
Praia Cabo Verde 14,93°N/23,51°W	T_{mean}	ºC	22.9	22.9	23.6	23.9	24.7	25.5	26.1	27.1	27.4	27.2	26.1	24.1	
	Tmin	ºC	19.3	19.2	19.5	19.9	20.7	21.6	22.7	23.9	24.2	23.6	22.5	20.8	
	Tmax	ºC	26.5	27.0	28.1	28.2	28.9	29.6	29.6	30.4	30.9	31.0	29.7	27.7	
	HR	%	65.7	63.3	62.6	64.5	65.2	68.5	73.3	76.0	76.8	72.9	69.8	70.1	
	SR	MJ/m²/d	16,6	18,9	22,6	24,2	26,3	25,8	22,6	20,9	19,4	18,2	16,3	14,9	
	Rainfall	mm	3.1	0.6	0.3	0.0	0.5	0.0	8.0	60.4	60.9	31.0	2.7	5.0	172.5
N'djamena Chad 12,11°N/15,0 7°E	Tmean	ºC	23.4	25.9	29.9	32.9	32.9	30.9	28.3	27.0	28.2	29.4	26.8	24.2	
	Tmin	ºC	14.3	16.6	21.0	24.8	25.8	24.7	23.1	22.4	22.7	21.8	17.8	14.8	
	Tmax	ºC	32.4	35.2	38.7	41.0	39.9	37.2	33.5	31.6	33.7	36.9	35.8	33.5	
	HR	%	29	23	21	28	39	52	68	76	72	49	33	31	
	SR	MJ/m²/d	18,9	21,3	24,0	24,2	23,5	22,3	19,9	19,1	19,9	19,9	18,9	17,5	
	Rainfall	mm	0	0	1	3	6	9	13	15	9	3	1	0	60
Abidjan, Ivory Coast 5,33°N/ 4,03° W	Tmean	ºC	26.8	27,7	27.9	27.7	26.9	25.8	24.7	24.5	25.6	26.8	27.4	27.0	
	Tmin	ºC	23.5	24.6	24.9	24.9	24.6	23.7	22.9	22.1	22.3	23.6	24.4	23.8	
	Tmax	ºC	30.5	31.0	31.1	31.2	30,4	28.7	27.4	26.9	27.6	29.2	30.5	30.3	
	HR	%	84	86	83	82	84	86	85	86	89	87	83	83	
	SR	MJ/m²/d	18,4	18,9	18,7	18,5	17,2	14,4	14,7	14,1	14,1	16,2	17,3	17,4	
	Rainfall	mm	3	4	9	11	19	22	12	8	11	14	16	9	138
Bissau, Guinea-Bissau 11,87°N/15,61°W	T_{mean}	ºC	24.4	25.6	26.6	27.0	27.5	26.9	26.1	26.4	26.4	27.0	26.9	24.8	
	Tmin	ºC	17.8	18.3	19.4	20.6	22.2	22.8	22.8	22.8	22.8	22.8	22.2	18.9	
	Tmax	ºC	31.1	32.8	33.9	33.3	32.8	31.1	29.4	30.0	30.0	31.1	31.7	30.6	
	HR	%	45,5	49	54	58	64,5	75	80,5	84	81,5	78	67,5	53,5	
	SR	MJ/m²/d	17,8	20,4	22,9	23,8	23,3	21,5	19,7	18,1	18,9	19,7	17,9	16,7	
	Rainfall	mm	0.5	0.8	0.5	0.8	17.3	175	472	683	435	195	41	2.0	2020
Conakry Guinea 9,54°N/13,68°W	Tmean	ºC	26,4	26,4	26,2	26,1	25,8	25,2	24,7	24,5	24,7	24,9	25	25,7	
	Tmin	ºC	22,8	22,8	21,4	20,2	20,6	20,4	21,4	21	20,4	19,8	20	21,4	
	Tmax	ºC	32.2	33.1	33.4	33.6	33.2	31.8	30.2	29.9	30.6	30.9	32.0	32.2	
	HR	%	56,6	61,9	66,7	73	82,3	86,4	86,8	87,3	87	86,5	83,1	66,7	
	SR	MJ/m²/d	20,1	21,8	23,7	23,3	20,3	17,6	14,8	14,2	17,6	18,6	18.5	18.9	
	Rainfall	mm	1	1	3	22	137	396	1130	1104	617	295	70	8	3784

City, Country	Data	Units	1	2	3	4	5	6	7	8	9	10	11	12	Total
Bamako Mali 12,65°N/8°W	Tmean	°C	24,8	27,9	30,9	32,5	31,4	28,6	26,3	25,7	26,1	27,3	26,9	24,9	
	Tmin	°C	16,6	19,8	22,8	25	23,8	22,2	20,6	20,4	20,2	19,6	18,8	16,8	
	Tmax	°C	33	36	39	40	39	35	32	31	32	35	35	33	
	HR	%	23,4	20,2	21,3	34,9	51,1	68,3	79,0	83,2	81,3	69	41,7	28,3	
	SR	$MJ/m^2/d$	18,8	21,8	22,6	23	22,1	20,5	18,9	18,2	19,3	20,2	20,1	191	
	Rainfall	mm	0,6	0,7	2,1	19,7	54,1	132	224	290	196	66,1	5,2	0,5	991,3
Nouakchott Mauritania 18,08°N/15,98°W	Tmean	°C	21,3	22,6	24	24	25,3	26,6	27	28,3	29,3	28,6	25,6	22,7	
	Tmin	°C	15,6	15,2	17	17	18,6	20,2	24	25,6	25,6	22,2	19,2	17,4	
	Tmax	°C	29.1	30.8	33.5	34.8	34.3	34.7	32.4	33.0	36.1	36.7	34.0	31.0	
	HR	%	38,5	43,3	49,6	59,2	60,1	67,0	75,9	75,7	71,3	56,9	48,3	40,8	
	SR	$MJ/m^2/d$	20,5	22,3	25,9	28,1	27,7	27,7	25,9	25,5	24,1	22,7	19,8	18,4	
	Rainfall	mm	0.7	1.5	0.2	0.1	0.3	1.9	6.3	36.8	36.3	6.3	2.0	2.8	95.2
Niamey, Niger 13,51°N/2,1°E	Tmean	°C	24,4	27,2	31,4	34,4	34,4	31,9	29,3	28	29,2	30,9	28,4	25,1	
	Tmin	°C	15,8	18,4	23,8	27,8	28,8	26,8	24,6	23	24,4	23,8	20,8	17,2	
	Tmax	°C	33	36	39	41	40	37	34	33	34	38	36	33	
	HR	%	21,6	17,4	17,0	25,3	40,9	54,5	66,9	74,7	69,5	47,1	27,4	24,4	
	SR	$MJ/m^2/d$	19,7	22,9	24,5	25,2	25,1	23,9	21,8	20,5	21,5	21,78	20,74	18,86	
	Rainfall	mm	0,0	0,0	3,9	5,7	34,7	68,8	154	171	92,2	9,7	0,7	0,0	540,7
Dakar, Senegal 14,69°N/17,44°W	Tmean	°C	20,7	20,7	21	21,4	22,8	25,6	27,1	27,4	27,6	27,6	25,8	23,4	
	Tmin	°C	15,4	16,4	17	17,8	19,6	22,2	27,2	24,8	24,2	24,2	21,6	18,8	
	Tmax	°C	26	25	25	25	26	29	27	30	31	31	30	28	
	HR	%	70,2	74,90	78,50	83,00	82,90	82,30	79,70	83,00	84,70	81,80	73,80	68,60	
	SR	$MJ/m^2/d$	17,6	20,9	23,6	24,9	24,2	22,4	20,2	19,2	19,2	19,9	17,9	16,5	
	Rainfall	mm	1,0	2,0	0,3	0,0	0,1	14,0	51,0	154	133	26	9,2	1,0	391,6
Ierapetra, Greece 35.01°N/25.74°E	Tmean	°C	13	13,3	14,7	17,3	21	25,8	28,3	28,1	25,1	21,7	18,3	14,8	
	Tmin	°C	9,7	10	11,5	13,9	17,3	22,2	24,4	24	21,4	18	14,7	11,6	
	Tmax	°C	16,3	16,6	17,9	20,7	24,7	29,4	32,2	32,1	28,8	25,4	21,9	18	
	HR	%	68	67	65	61	60	57	58	59	60	65	67	70	
	SR	$MJ/m^2/d$	8,3	10,9	14,7	18,6	22,6	25,9	26,3	24,5	19,7	13,9	10,4	8	
	Rainfall	mm	101	70,7	44,8	20	10,4	1,3	0,3	0,7	13,7	41,7	62,8	118	484,4

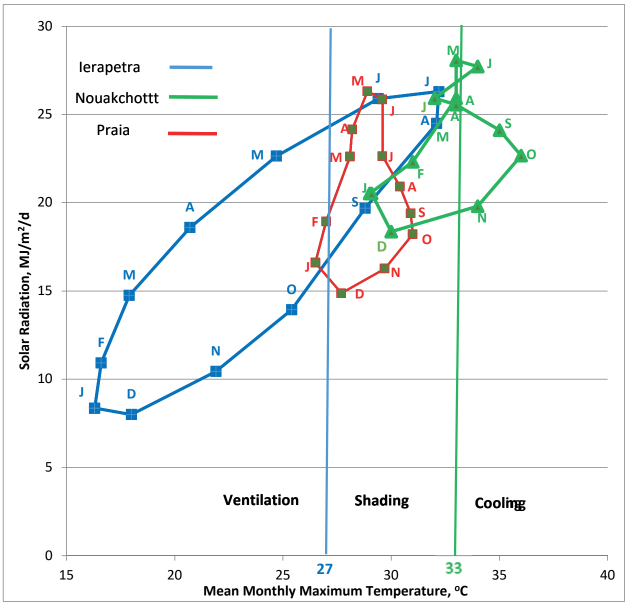

Fig. 2. Climograph of Nouakchott ((Mauritania, 18°09'N and 15°58'W, warm desert climate), Praia (Cabo Verde, 14°55'N and 23°31'W, warm desert climate) and Ierapetra (Greece, 35°00'42.70"N, 25°44'32.42"E, cold semi-arid climate).

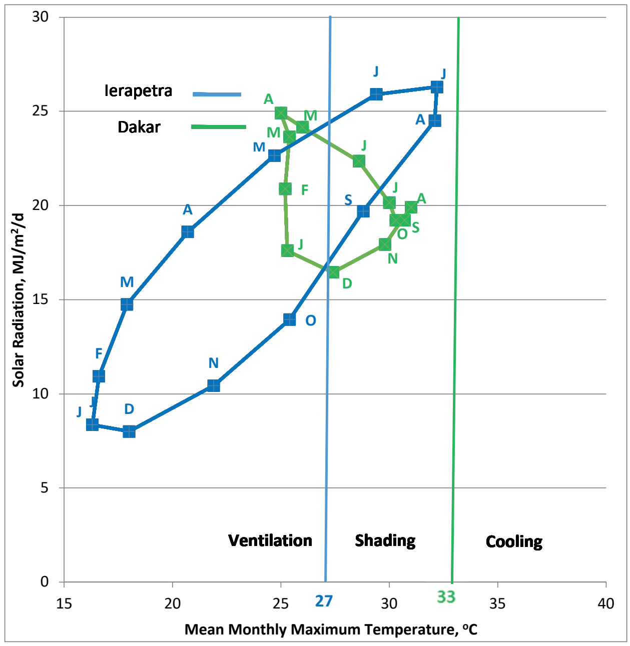

Fig. 3. Climograph of Dakar, Senegal, 14°40'N and 17°25'W, warm semi-arid climate) vs Ierapetra (Greece, 35°00'42.70"N, 25°44'32.42"E, cold semi-arid climate).

roof vents should be kept permanently open and shading of the greenhouse should be applied using nets with SI= 30%[4]. (iii) The combined action of natural ventilation and shading can increase the transpiration of the plants, which is beneficial for the crops due to the outside low humidity. It should be stressed that all ventilator openings must be covered with insect proof nets (50 mesh). (iv) From March to mid-November) an evaporative cooling system is necessary. . The diurnal relatively high air temperatures combined with the absence, practically, of rainfall lead to diurnal values of air relative humidity no greater than 30- 40%. Consequently, a satisfactory performance of an evaporative cooling system is assured for a greenhouse installed in such an area (Watson et al., 2019).

However, this requires additional investment for more sophisticated technical options like fan and pad cooling, or a high-pressure fog system, both of which also improve the hygrometric status of the greenhouse environment. Fan and pad greenhouse cooling is based on hot and dry air being sucked through a wet pad posed at one side of the greenhouse and electric ventilators at the opposite site (Franco et al., 2014). The high pressure fog cooling system occurs by spraying a fine mist that will evaporate and cool down the air by absorbing the heat inside the greenhouse[5] (Kumar et al., 2009). The use of photovoltaic panels for powering the ventilators and the pump is an option that has to be validated as a cost effective investment.

The climate in Praia (Cabo Verde) is also classified warm desert. However, as compared to Nouakchott the maritime effect is pronounced and induces lower temperatures and even less rainfall. Figure 2 shows that shading of greenhouses is necessary throughout all the year. Furthermore, the shading has a beneficial effect since it enhances transpiration of stressed crops. Black plastic mulching against weeds is advisable. It will reduce inside air humidity and help to prevent fungal diseases.

b. Climograph of Dakar vs Ierapetra

The climate in Dakar (Senegal) is warm semi-arid (BSh). Figure 3 shows that for half of the year, from December to May, a very good ventilation is sufficient. For the rest six months shading is necessary. Nevertheless, considering that insect proof nets in the ventilation openings against insects are indispensable, shading of greenhouses throughout all the year is suggested to avoid too high temperatures inside.

[4] SI: Shading Intensity

[5] The latent heat of evaporation of water at 25°C is approximately 2500 J/g, it means that evaporation of 1 gram of water at 25 °C will absorb approximately 2500 Joules (580 calories) from the ambient air

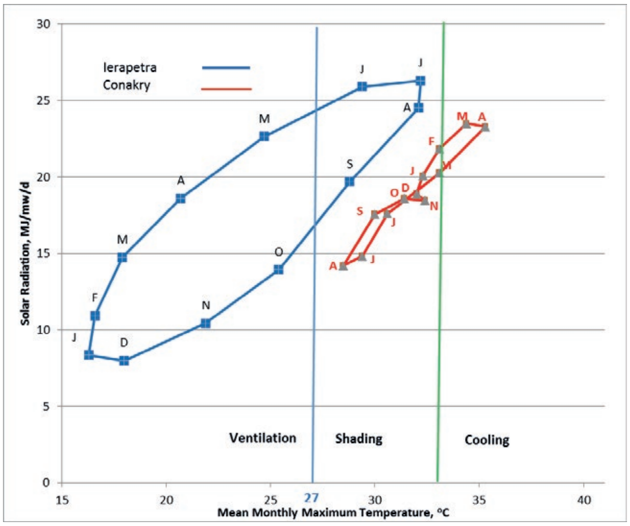

Fig. 4. Climograph of Conakry (Guinea, 9°31'N and 13°42'W, monsoon climate) and Bamako (Mali, 12°39'N and 8°0'W, tropical savanna) vs Ierapetra (Greece, 35°00'42.70"N, 25°44'32.42"E, cold semi-arid climate).

c. Climograph of Bamako and Conakry vs Ierapetra

The climate in Bamako (Mali) is tropical savanna and in Conakry (Guinea) it is monsoon.

From Figure 4 we can conclude and suggest:

For Conakry: Cultivation is possible from June to February (9 months), in a greenhouse, equipped with efficient ventilation system and shading. For the rest of the year i.e. from mid-February to mid-May, the mean maximum temperatures are slightly over 33°C. Such mean maximum temperatures, for a short period, do not justify the use of an evaporative cooling system, taking into consideration its cost and low efficiency due to the high outside relative humidity (HR>60%). So, it may eventually be possible to produce vegetables in Conakry all year round under greenhouses the higher ,the better(gutter at least 3.5-4 m), with roof openings and the whole lateral side opened and an external roof shade net with a S.I. of 30-35 %. The ventilation openings must to be equipped with nets to protect against insects, birds, and rodents, and should be increased by at least 10% to reach 40% of the floor area in order to avoid decreasing the ventilation efficiency too much.

For Bamako, the case is a more difficult:

- From October to June (9 months), it is necessary to cool the greenhouse by using for example the fan and pad system since outside temperatures are too high The corresponding outside humidity during this period is low, which favours an efficient evaporative cooling system.
- The rest of the year i.e. from July to September (3 months), it is possible to produce vegetables under greenhouses the higher, the better (gutter at least 3.5-4 m), with roof openings and the whole lateral side opened and shade net with a SI of 30%. The ventilation openings must to be equipped with nets to protect against insects, birds, and rodents, and should be increased by at least 10% to reach 40% of the floor area in order to avoid decreasing the ventilation efficiency too much.

Summing up for greenhouse types

From the analysis, using the climagraphs of the above mentioned cities for characterising the suitable greenhouse types, it can be concluded that for RADHORT countries:

- In warm desert and warm semi arid areas (BWh and BSh) a greenhouse should be the highest possible (resistant enough to strong winds), equipped with lateral and roof vents, with openings corresponding to 30-35% total floor area, permanently opened throughout all the year and always equipped with shade nets SI 30%. Additionally, in continental BWh areas an evaporative cooling system is necessary for 3-4 months during the year.
- In tropical savanna (Aw), greenhouses with combined rooftop ventilation and shading system could be sufficient for 7 to 9 months. An evaporative cooling system (fan and pad or high-pressure fog) is necessary for the rest of the year (3 to 5 months) in such areas. For monsoon (Am) climate areas it could be possible to produce vegetables all year round in greenhouses: the higher possible, with combined roof and lateral ventilation openings of a total ventilation area equivalent to 40% of the floor area permanently opened and covered with insect proof nets and the roof shaded with nets of SI of 30%.
- In the Sahelian environment of the RADHORT countries, an adapted greenhouse should be:
  - High (2.5-3 m minimum at gutter height) and must have:
  - Lateral and roof openings of 30-35% of the total floor area needed for good ventilation, covered with 50 mesh insect proof nets and remain permanently open.
  - Shading nets on roof with SI≈30%
  - Plastic or straw mulching.
- For all options, plastic or straw mulching would provide additional advantages for saving irrigation water and reducing the relative humidity inside the

greenhouse and helping to control fungal diseases and weed growth.

These types of greenhouses and equipment recommended for the RADHORT climate environment are different from the greenhouses successfully used in Ierapetra. This illustrates the fact that greenhouses and their management have to be "tailored" to the local conditions and needs.

NETHOUSES IN TROPICS

Nethouse cultivation may constitute an alternative, to open field production in warm climates. It could be a less expensive option than greenhouse cultivation. Nethouses are usually covered with shade nets and SI of 20-30% or with insect-proof screens[6] of 50 mesh, i.e. 50 open spaces per inch in each direction, delineated by the threads.

Insect-proof nets are recommended, in order to avoid insect damage and thereby limit the use of plant protection products. For many advantages, nethouses are used to (Kitta, 2014):

- reduce high radiation levels and wind speed;
- modify positively the crop physiological response due to relatively good ventilation and adapted shading avoiding too high temperatures . The inside air temperature should not be very different from the temperature outside;
- lead to enrichment in diffuse radiation inside the growing environment, resulting in better uniformity and higher level of radiation captured by the plants;
- keep the leaf temperature lower as compared to the open field thereby avoiding photo-synthesis inhibition;
- protect against sunburns, that affect the quality of the produce;
- protect the crop from hail, sand storms, and physical damage caused by heavy rain;
- minimize the invasion of insects, thus, allowing a significant reduction in plant protection products application;
- avoid the entrance of different types of predators, including birds and rodents.

All the above advantages lead to increased overall yield levels of better quality, reduced water consumption and increased water use efficiency (WUE) and water productivity (kg/m^3). Related experiments in warm Mediterranean climates show that the production in nethouses is almost doubled (for tomatoes from five to ten kg per m^2), and water consumption is reduced by 40% (Kitta et al., 2014b). Similar results were mentioned by Saidi et al. (2013) for tomato growing under nets in East Africa climate (Njoro-Kenya, temperate Mediterranean climate classified as Csb by the Köppen-Geiger system). Furthermore, Simon et al. (2014) found similar results for cabbage under nets in Mediterranean climate (Montpellier, Csa climate type), instead for subequatorial climate (Cotonou Benin, tropical savanna climate, classified as Aw by the Köppen-Geiger system), they propose periodical removal of nets (during the rainy season), to increase productivity.

In terms of productivity, the best shading or insect proof net is white with shading intensity between 20 and 30% (Kitta et al., 2014). However, it is important to note that nethouses are shelter options that are efficient for production essentially outside the rainy periods.

In conclusion, compared to a greenhouse, a nethouse is a relatively simple and cheap construction. Associated to adequate horticultural techniques and practices (quality seed and planting material, irrigation, fertilization and integrated phytosanitary protection), it is a production technology that leads to a significant increase of crop yield and quality, and the efficient use of water and other inputs, when operated, in the tropics, outside the raining period.

Attention must be paid to the fact that nethouses protect, to a certain extent, against restrictions and constraints of open field production. It should be emphasized that the only device used for climate modification is the covering net. Nethouses are basically different from greenhouses, which are more capital expensive but more efficient and more flexible when equipped appropriately with climatic control devices according to the investment potential in each case. According to von Zabeltitz (2011), the plants under nethouses are permanently wetted when raining, which favors diseases occurrence. Therefore, nethouses may be limited to regions with very low rainfall during the cropping season.

Appropriate Nethouses for Sub-Saharan (RADHORT) countries

The suitability of nethouse cultivation in RADHORT countries, is based on the following analysis.

a. For Nouakchott, Mauritania (18°09'N, 15°58'W, warm desert climate BWh), taking into account that there is almost no rainy period in the desert climate of Nouakchott and simultaneously the outside maximum temperatures, are not excessive from

[6] Insect proof screens of 50 mesh have a SI of about 20%

mid-November till July (Fig. 2), growing vegetables under a nethouse covered with insect proof nets or shading nets is proposed, as a valuable alternative solution to open field production. For the rest of the year, between July and mid- November it would be possible to produce vegetables under nethouses by growing heat resistant species, like sweet potato. Therefore, it is possible to grow vegetables under a nethouse year round with satisfactory yield levels, provided water for irrigation is secured. In fact, for desert areas of RADHORT countries, the limiting factor for vegetable cultivation is not only the climate but also the water availability. If we consider that the incoming solar radiation is more or less stable for Nouakchott and in the order of 20 MJ/m^2/day, the water needs (E) for a vegetable production under a nethouse with a transmissivity factor of 70% (so, shading intensity of 30%) is of about:

E=0.67*0.7*20/2.5=3.8 mm/ day= 3.8 l/m^2/day.[7]

So, for a growing vegetable season of 150 days, 571.5 mm of water are needed. For two production cycles, the total amount of water needed is 1143 mm, equivalent to 1,143 l/m^2 (1,143 m^3/m^2) for a production cycle of 300 days.

From available climate data, the total precipitation quantity for Nouakchott is only 94 mm and therefore, even if all the rainwater is collected, this quantity covers only about 13% of the water needs for irrigation. So, the irrigation should be based on well or river water, mainly from the Senegal River.

b. For Dakar, Senegal (14°40'N 17°25'W, warm semi-arid climate, BSh) and Praia, Cabo Verde (14°5'N 23°31'W, warm desert climate, BWh), we can conclude from climate data of Table 1, that, due to the raining interval, the convenient period for vegetables under nethouses is from November to June-July, practically for a period of 8 months, since the rainy season usually extends from July to October (4 months). However, a possible solution to extend the growing period during the rainy season, could be to cover only the roof of the nethouse with a removable 50 micron-thick transparent polyethylene film[8]. This may result, however, in reducing light transmittance by two cladding materials. (von Zabeltitz, 2011). The temperatures in non-raining period are convenient for vegetable production under nethouses provided that water for irrigation is available. Giving that the radiation regime in the BWh and BSh climate zones is about 20 MJ/m^2/day, a total quantity of water for a vegetable production in nethouses for a period of 8 months, is around 900 mm (= 240*0.67*0.7*20/2.5) or 0,900 m^3/m^2. For Dakar, almost half of this quantity could be captured from harvesting the rainwater, which is about 400-500 mm/year, mainly from the roofs of adjacent buildings and eventually stored in farm ponds lined with plastic taking into account that farm ponds have some important limitations , like cost and space. The remaining half could be pumped either from rivers or from aquifers. In Praia, because of the prevalence of salty underground water, the situation is more difficult since the only source of water could be from collecting rainwater[9], which, nevertheless, is less than 200 mm/ year. For covering the water needs of a 9-month vegetable production cycle, about 1,0 m^3/m^2 of nethouse is needed. (=270*0.67*0.7*20/2.5).

c. For Conakry, Guinea (9°31'N; 13°42'W, monsoon climate Am) and Bamako, Mali (12°39'N; 8°0'W, tropical savanna climate, Aw) the raining period is extended from May to October. Therefore, only a limited period of 6 months (from November to April) is suitable for vegetable production under a nethouse. In Am and Aw climates, there is no problem of water availability due to abundant rainwater quantity provided it is properly harvested. However, in these climate zones, abundant and heavy rainfall can also be a limiting factor, besides the high temperatures regime occurring during the non-raining period. Therefore, possible period for nethouse vegetable production is short, only 6 months (between November and April) with an increased shading factor in the order of 40%, but with eventual risk of lower productivity. For the other six months, a nethouse is not well adapted. Vegetable production in the rainy season can be improved by growing in a greenhouse as rain-shelter with roof ventilation and open sidewalls. An alternative option, less expensive, would be to cover only the roof of the nethouse with a removable transparent IR reflectant polyethylene sheet of 50 micron.

[7] According to de Villele (1974) the following simplified relation can be used for the estimation of water needs (E) of crops under cover in Mediterranean areas: E = K 0.67 t RSo /λ (mm/day), where: K = crop coefficient, t = transmissivity of the cover to solar radiation, RSo = outside solar radiation (MJ m^{-2} day^{-1}), λ = latent heat of vaporization of water (=2,5 MJ/mm/m^2)

[8] The polyethelene file should possibly be an NIR reflective in order to reduce the transmission of SR and thereby avoiding the overheating of the greenhouse

[9] On the Island of Santiago and other Islands of Cabo Verde rainwater is stored in retention ponds and small lakes behind dams in the mountainous areas.

Summing up for nethouse cultivation in RADHORT countries

In all 5 cities people grow vegetables during the rainy season in the open field particularly leafy vegetables like amaranth, nightshade and also fruit vegetables like okra and root vegetables like sweet potato.

Practically speaking, a nethouse is useful all year round. Additional protection against the rain could be obtained by covering only the roof of the nethouse with a PE film of 50 micron. This can suffice for a few months in climates of Dakar and Praia (BSh) and maybe not needed in Nouackchott (BWh). Instead in Bamako (Aw) and Conakry (Am), a nethouse with a permanent covered roof, will be more adequate to contain the impact of the extended rainy season on the crops.

In conclusion, growing vegetables under a nethouse is possible in all climates and seasons of the RADHORT countries. It is a technological progress as compared to growing in open field without any means of protection. It offers the different advantages as cited by Kitta, 2014. To protect the crop against the rain, it is possible but not compulsory, to cover the roof of the nethouse with a PE film of 50 micron during the rainy season.

ECONOMIC ASSESMENT FOR SHELTERED CULTIVATION IN RADHORT COUNTRIES

From an economic point of view, the cost of inputs will largely vary according to the countries and cities within the countries and the volatility of market prices for imported items. Prices for structure components can be lower when sourced from local markets. Indicatevely, for Spain (Almeria) and Greece (Ierapetra), the investment for a simple greenhouse equipped with only static ventilation, drip irrigation system and shading nets (no cooling) ranges from 15 to 17 €/m^2 and the corresponding net profit for tomato production is of 5 to 6 €/m^2/year. The corresponding investment for a nethouse varies between 7 to 8 €/m^2, incluging the structure, covering net and drip irrigation pipes, with a net income for pepper production of the order of 2 to 3 €/m^2/year. Considering that cost of a technology package of sheltered cultivation will vary according to countries and areas, the return on investment will also be case specific.

The promotion of sheltered horticulture in RADHORT countries would require business case studies, which would be used to document and justify the access to credit and eventual subsidies to facilitate the adoption of innovative production technologies in support of sustainable horticulture intensification.

Factors to consider in order to asses the return on investment are, *inter alia*:

- higher yield levels per unit of area, as a result of year-round cultivation;
- higher income per unit of area, as a result of precision production planning in accordance to market demand and better prices;
- better quality and higher proportion of marketable yield;
- higher income as a result of premium prices obtained in niche markets for quality and labeled produce, which offers traceability;
- higher water productivity (less expenses for water and energy per kg of produce);
- higher labor efficiency (all days can be working days);
- less expenses for chemical pest and disease control;
- less dammage by birds, rodents and other predators;
- less expensive and easier weed control;
- less fertiliser requirements, as a result of reduced drainage of soluble minerals;
- less physical damage to crops due to heavy rain and wind;
- use of high quality seeds and/or seedlings of adapted cultivars;

CONCLUDING REMARKS

Vegetable production in RADHORT countries can be intensified and the quality improved by adopting adequate shelter structures and covering materials. The demand for vegetables is rapidly increasing in light of the population growth and the urbanization process. With improved health consciousness, the demand for quality vegetables is expected to further rise over time with higher pro-capita consumption, which today is far below the 400 grams of daily intake, as recommended by WHO-FAO. However, sheltered horticulture in the RADHORT area is still very limited and in most cases non-existent with only some exceptions.

Based on cost-benefit analysis, sheltered horticulture should be further investigated as an option to reduce the use of plant protection products, while increasing productivity and quality per unit of land and water. At the same time, it will foster entrepreneurship and create additional job and income opportunities for prospective farmers, women and youth.

Moreover, there are obvious environmental challenges for enhancing the development of sheltered horticulture. The most important are: the non- chemical protection of vegetables against insects, diseases and weeds with physical means such as insect proof nets, appropriate cover and mulching; the reduced water consumption for irrigation. By increasing the productivity by unit of land area, the encroachment on nature is contained. On the other hand, a negative environmental impact of sheltered horticulture is mainly related to the use and disposal of plastic waste. However recycling processes help to wave this inconvenience.

Ultimately and importantly, increasing the production of high quality fruit and vegetables all year round in sheltered cultivation, will contribute to attaining the Sustainable Development Goals (SDGs) of the United Nations (2015), essentially SDG 2 for improved food and nutrition security and SDG 1, reducing poverty, while protecting the environment and human health. As such, sheltered cultivation complies with the agroecology principles. Low- tech, cost-effective, properly designed greenhouses and nethouses constructed using locally available materials, whenever available, is a promising choice for the smallholders especially in urban and peri-urban areas of RADHORT's cities, to meet the increasing market demand for fresh vegetables. However, in order to be applied rationally, its development should be paired with capacity building and applied research, backed up by policy support and mobilization of needed resources including incentives and easy access to credit.

Sheltered horticulture is proposed as a regional thematic subject area for research, capacity building and development, to be implemented on the basis of the RADHORT regional cooperation agreement and commitment.

REFERENCES

Baudoin, W.O., von Zabeltitz, C.H.R. 2002. Greenhouse constructions for small-scale farmers in tropical regions. Acta Hortic. 578: 171-179.

de Villele, O. 1974. Besoins en eau des cultures sous serre- Essai de conduite des arrosages en fonction de l' ensoleillement. Acta Hortic. 35, 123-135. DOI:0.17660/ActaHortic.1974.35.16

Duhan, P.K. 2016. Cost benefit analysis of tomato production in protected and open farm. International Journal of Advanced Research in Management and Social sciences. 12(5): 140-148.

FAO, 2016. Réseau Africain pour le Dévelopement de l'Horticulture (RADHORT). http://www.fao.org/3/a-i5719f.pdf.

Climate map. http://www.synergy-energy.co/africa-climate-map.html

FAO, 1999. C. von Zabeltitz, W.O. Baudoin. Greenhouses and shelter structures for tropical regions. https://scholar.google.it/scholar?q=fao+agp+paper+154.

Franco, A., Valera, D.L., Peña, A., 2014. Energy Efficiency in Greenhouse Evaporative Cooling Techniques: Cooling Boxes versus Cellulose Pads. Energies, 7: 1427-1447.

Katsoulas, N., Rigakis, N., Kitta, E., Baille, A. 2012. Transpiration of a sweet pepper crop under screenhouse conditions. Acta Hortic. 957: 91-97.

Kitta, E. 2014. Ecophysiological and Agronomic Response of Horticultural Crops Grown under Screens in a Mediterranean Climate. PhD Diss., Polytechnical University of Cartagena, Spain.

Kitta, E., Baille, A., Katsoulas, N., Rigakis, N., González-Real, M.M. 2014a. Effects of cover optical properties on screenhouse radiative environment and sweet pepper productivity. Biosystems Engineering, 122: 115-126.

Kitta, E., Baille, A., Katsoulas, N., Rigakis, N. 2014b. Predicting reference evapotranspiration for screenhouse-grown crops. Agricultural Water Management, 143: 122-130.

Kittas C. 1995. A simple climograph for characterizing regional suitability for greenhouse cropping in Greece. Agricultural and Forest Meteorology, 78: 133-141.

Köppen, W.P. 1936. Das geographische System der Klimate. Handbuch der Klimatologie, W.P. Köppen and R. Geiger, Eds., Vol. 1, Part C, Gebrüder Borntraeger, C1-C44.

Kumar, K.S., Tiwari, K.N., Madan K. Jha, 2009. Design and technology for greenhouse cooling in tropical and subtropical regions: A review. Energy and Buildings 41: 1269-1275

Nederhoff, E. and Stanghellini, C., 2010. Water Use Efficiency of Tomatoes. Practical Hydroponics and Greenhouses, (115): 52-59. https://search.informit.org/doi/10.3316/informit.484066941930798

Saghir, J., Santoro, J. 2018. Urbanization in Sub-Saharan Africa. Meeting Challenges by Bridging Stakeholders. Report of Project on prosperity and development. Center for Strategies & International Studies. 7 pp.

Saidi, M., Gogo, E.O., Itulya, F.M., Martin, T., Ngouajio, M. 2013. Microclimate modification using eco-friendly nets and floating row covers improves tomato (Lycopersicon esculentum) yield and quality for small holder farmers in East Africa. Agric Sci 4(11): 577-584.

Simon, S., Komlan, F., Adjaïto, L., Mensah, A., Coffi, H.K., Ngouajio, M., Martin, T. 2014. Efficacy of insect nets for cabbage production and pest manage-

ment depending on the net removal frequency and microclimate. Int J Pest Manag 60(3): 208-216.
United Nations, 2015. Transforming our world: the 2030 Agenda for Sustainable Development, 41 pp.
von Zabeltitz, Ch., Baudoin, W.O. 1999. Greenhouses and Shelter Structures for Tropical Regions. Food and Agriculture Organization of the United Nations, FAO Plant Production and Protection Paper 154, Rome: FAO.
von Zabeltitz, Ch. 2011. Integrated Greenhouse Systems for Mild Climates Climate Conditions, Design, Construction, Maintenance, Climate Control. Berlin Heidelberg: Springer-Verlag.
Wachira, J.M., Mshenga, P.M., Saidi, M. 2014. Comparison of the profitability of small- scale greenhouse and open-field tomato production systems in Nakuru-North District, Kenya. Asian J Agric Sci 6(2): 54-61.
Watson, J.A., Gómez, C., Bucklin, R.A., Leary, J.D., McConnell, D.B. 2019. Fan and Pad Greenhouse Evaporative Cooling Systems. CIR1135 Technical Report, University of Florida.