FELLOWSHIP SUMMARY REPORT

Name: **Francisco Domingo MOLINA-AIZ**
Subject of the research fellowship: **Assessment and improvement of carbon sequestration in greenhouse horticultural crops.**
Theme: **Transformational Technologies and Innovation (Theme 3)**
Host institution: **Wageningen University & Research (WUR)**
Host supervisor: **Silke HEMMING**
Dates of the research fellowship: **14 February 2022 – 17 June 2022**

I consent this Summary Report be put on the Co-operative Research Programme's website.

FELLOWSHIP SUMMARY REPORTS

1. What were the objectives of the research project? Why is the research project important?

The main objective of the research developed at Wageningen University and Research Centre in the Netherlands under the supervision of Dr. Silke Hemming and the coordination of Dr. Feije de Zwart was to improve knowledge about the CO_2 sequestration capacity of greenhouse horticultural crops and to study the use of new technologies to increase photosynthesis. The spatial distribution of the photosynthetic activity of tomato, pepper and cucumber crops in naturally ventilated greenhouses have been modelled using Computational Fluid Dynamics (CFD). The CFD model allows to simulate plant photosynthesis from the outside solar radiation and inside CO_2 concentration and the structural characteristics of the greenhouses. Simulations have been validated through experimental measurements carried out on the 2021/22 season in greenhouses of the University of Almería (UAL). Measurements in greenhouses included the main outside and inside climate parameters (air temperature and humidity, air velocity, solar radiation and CO_2 concentration), photosynthetic activity, photosynthetically active radiation, transpiration and stomatal conductance. CFD models are an effective tool to analyse different design or control options of climate control systems in greenhouses. In this case CFD simulations have been used to analyse the effect of low-cost technologies such as the increase in the side opening surface or the use of double roofs as an alternative to the traditional whitewashing of the roof of Mediterranean greenhouses.

This research project is important because augmentation of photosynthesis can contribute to the sustainability of greenhouse systems by increasing crop productivity and therefore reducing the use of inputs (energy, water and nutrients) per unit of produce. Given that there is little information about the amount of CO_2 captured by greenhouse crops, it was also intended to quantify the amount of carbon absorbed by plants photosynthesis in greenhouses. As a result of the short cycle of horticultural crops, the absorption of CO_2 through photosynthesis does not contribute directly to the reduction of its atmospheric concentration. Only if energy is obtained from plant waste and its use allows us to reduce the application of fossil fuels, photosynthesis could indirectly contribute to not further increasing the concentration of atmospheric CO_2.

2. Were the objectives of the fellowship achieved?

Or are they on the way to being achieved?
If not, for what reasons? (The data or research is still ongoing or being analysed; technical reasons (e.g. equipment not working, adverse weather conditions, unexpected results, etc.; other reasons?)

The main objectives of the fellowship have been partially achieved since the results obtained will be completed with those of the experimental measurements currently underway. During the fellowship, the values of the instantaneous CO_2 capture of tomato and cucumber crops developed in previous years (2018 and 2021) have been calculated from photosynthesis measurements in the leaves of plants (Jiang *et al*., 2017) and from the estimation of the flow of CO_2 in the greenhouse, measuring air velocity and CO_2 concentration in the greenhouse openings (Teitel, 2017). The amount of carbon absorbed in the tissues of the crops (both of the plants at the end of their life, and of the fruits harvested throughout the productive period) has also been calculated. For this, values of the ratio of carbon content/dry matter obtained from the literature have been used (Mota *et al*., 2010).

Next July 2022 the pepper crop will end that is currently being developed in 4 experimental greenhouses of the University of Almeria. At the end harvest, the fresh and dry weight of the different parts of several pepper plants will be measured. In the same way, the fresh and dry weight of the fruits harvested in the different yields are being measured. In addition, the carbon content of the samples of the new pepper crop and samples of the previous crops (currently stored at the University of Almería) will be determined from laboratory measurements. New experimental airflow and photosynthesis measurements will also be carried out with the pepper crop for the validation of the CFD models developed during the fellowship.

3. What were the major achievements of the fellowship? (up to three)

One of the main objectives achieved during the fellowship has been the development of CFD three-dimensional models of greenhouses with natural ventilation including the photosynthesis of the crop. Until now, only two CFD

models have been developed that include plant photosynthesis. One of the models corresponded to a semi-closed and closed greenhouses with artificial CO_2 injection (Roy *et al*., 2014; Boulard *et al.*, 2017). The second was the 2D model developed by Molina-Aiz *et al*. (2017) in an *Almeria*-type greenhouse with natural ventilation. The new models developed during the fellowship contain several improvements. Being a 3D model that includes the outside air around the greenhouse (Fig. 1), it was possible to analyse the effect of wind direction on the spatial distribution of climatic parameters within the greenhouse (temperature, humidity, CO_2 concentration and air velocity) and its influence on transpiration and photosynthesis of the crop. In addition, the model was expanded by describing two greenhouses with side and roof openings with a separation of 3 m in between simultaneously (Fig. 1). This allows to observe how air that comes out of the windward greenhouse (with high humidity due to the transpiration of the crop and lower concentration of CO_2 due to the absorption by plants photosynthesis) enters through the openings of the leeward greenhouse, and how it affects the activity of the crop in this second greenhouse

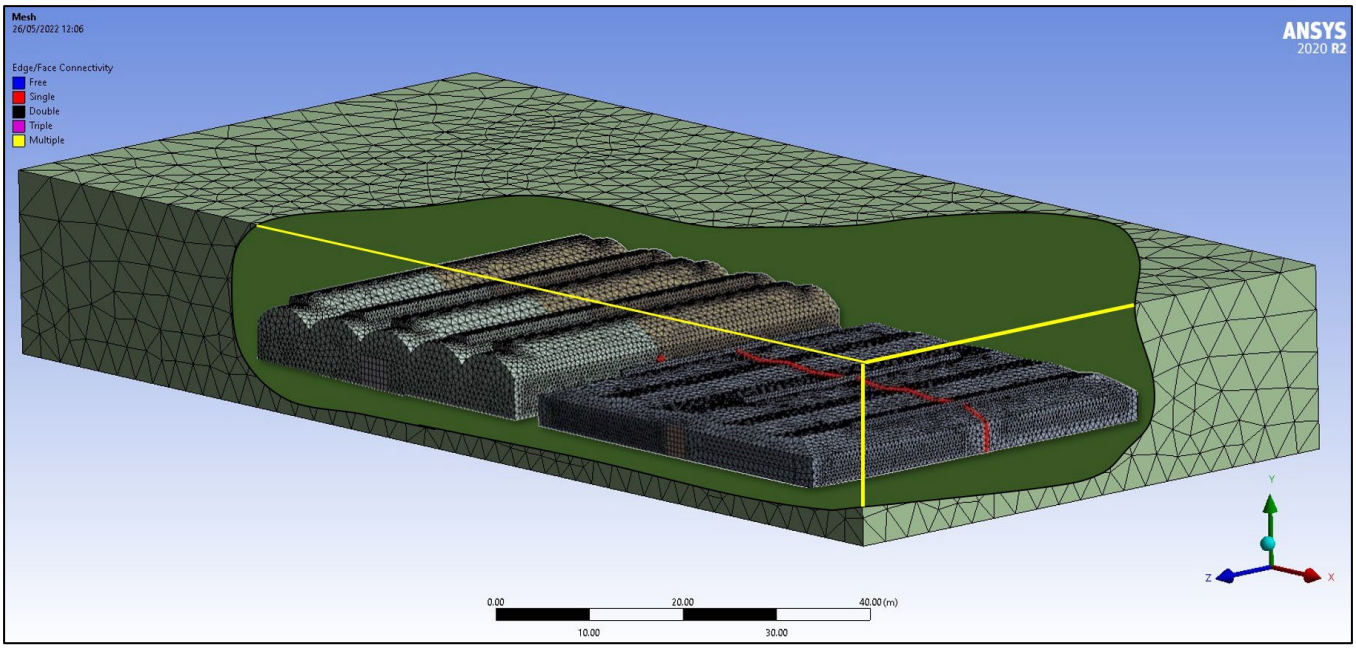

Figure 1. Computational domain of the CFD model with an *Almería*-type and an adjacent multispan greenhouses.

Another objective achieved with the work developed during the fellowship has been the estimation of the capture of CO_2 in the tomato and cucumber plants in greenhouses (Table 1). In literature there are references of this type of data for fruit crops (Wu *et al*., 2012; Scandellari *et al*., 2016; Sharma *et al*., 2021), but very little information on horticultural crops (Mota *et al.*, 2010). The data obtained correspond to production levels close to the average values of commercial greenhouses and are therefore more representative for the productive sector than those referenced in the literature (Mota *et al.*, 2010). This type of data is of great interest in works of Life Cycle Assessment (LCA) or circular economy.

Table 1. Fresh weight (FW), dry matter (DM) and estimation of carbon content of biomass in tomato and cucumber plants.

Plant parts	FW	DM	DM/FW	Carbon *	Carbon	C in fruits	CO_2
	[g plant^{-1}]	[g plant^{-1}]	[%]	[% DM]	[g C plant^{-1}]	[g C plant^{-1}]	[g m^{-2}]
Tomato 2018	18819	2162	11.5	41.6	978	849	3982
Tomato 2021	8058	758	9.4	41.6	331	193	1212
Cucumber 2021	9857	481	4.9	41.6	212	143	777

* Carbon proportion obtained from Mota *et al*., 2010.

4. Will there be any follow-up work?

- Is a publication envisaged? Will this be in a journal or a publication? When will it appear?
- Is your fellowship likely to be the start of collaboration between your home institution and your host?
- Is your research likely to result in protected intellectual property, novel products or processes?

Part of the work developed has been included in two papers that have been submitted to the 31st International Horticultural Congress IHC 2022, 14-20 August 2022, Angers (France), entitled "*Experimental and numerical assessment of carbon sequestration in horticultural crops inside Mediterranean naturally ventilated greenhouses*" and "*Use of augmented natural ventilation and 'double roof' with photoconversion films to improve crop photosynthesis inside greenhouses*". In these two papers, the aid received by the OECD is mentioned, but participants from Wageningen University have not been included as authors, since the authors were proposed to the congress prior to the stay. Once the project will be completed in the next month with the data of the pepper crop currently in development at the University of Almería, two additional publications entitled "*Experimental assessment of carbon sequestration in horticultural crops inside Mediterranean naturally ventilated greenhouses*" and "*Modeling of spatial variability of photosynthesis crops inside naturally ventilated horticultural greenhouses with Computational Fluid Dynamic*" will be submitted to the journals *Sciencia Horticulturae* and *Agricultural and Forest Meteorology*, respectively, in which the researchers of the Wageningen University & Research (WUR) who have participated in the analysis and discussion of the results will be included.

The fellowship has helped to strengthening the exchange of ideas and increasing international mobility and co-operation between the two research institutions (UAL and WUR) with common expertise on the field of energy saving, greenhouse climate, water saving, modelling and sensors for greenhouse applications. Greenhouse production represent an important economic sector in both Almería and the Netherland. The fellowship has allowed to find several topics of common interest in which to continue collaborating in the coming years. One of the main topics of common interest has been the analysis of new materials used in greenhouse covers, in energy-saving screens or shading nets to modify the spectrum of the light absorbed by plants. Another point of common interest has been the quantification of the carbon content in horticultural crops, necessary information for the work that is developed by WUR on horticultural production for a circular economy. A third topic of collaboration is the integration of plant models into climate control models for greenhouses. Finally, another topic of special interest to both institutes is the development of Computational Fluid Dynamics models for the study of cooling systems in greenhouses in arid and semi-arid climates.

In addition to the collaboration in the development of research work in the future, we will maintain a collaboration with several of the members of the group Greenhouse Technology in which the fellowship has been developed, as well as other researchers from Wageningen University from the group Horticulture and Product Physiology, as part of the scientific committees of two international congresses of which I am one of the conveners. The first congress will be the *HorchiModel 2023 International Symposium on Models for Plant Growth, Environments, Farm Management in Orchards and Protected Cultivation* that will be held at University of Almería (Spain) from June 26th to 28th 2023. Two years later we will also organise at the UAL the *Geensys 2025 - International Symposium on New Technologies for Sustainable Greenhouse System* that will be held from 22th to 26th June 2025.

All the work developed during the fellowship has been based in the analysis of experimental data previously carried out at the University of Almería and developments of numerical models, so it has not resulted in any protected intellectual property.

5. How might the results of your research project be important for helping develop regional, national or international agro-food, fisheries or forestry policies and, or practices, or be beneficial for society?

Please express this in terms of environmental/food security/food safety/economic/health (human and livestock and plant) benefits, etc.

The research developed is focused in the evaluation and improvement of the capacity of horticultural greenhouses to grow plants with atmospheric CO_2. This information could contribute to inform policy makers in the development of policies relatives to greenhouse industry, promoting new technologies that can enhance it. Increasing the

photosynthesis of horticultural crops using passive climate control systems, which require a small economic investment, can have a positive impact on the economic balance of the farms improving its long-term sustainability. On the other hand, a better use of solar energy by crops means being able to increase productivity per unit of inputs used, reducing the amount of water and nutrients needed per kg of product obtained and land use by achieving more production per m^2.

It is important to know the amount of carbon stored in greenhouse crops waste because they have significant energy potential. Proper use of greenhouse plant waste to generate biofuels can help reduce the use of fossil fuels. This waste can also be an important source of nutrients for the plants. Organic crop waste in landfills generates methane, a potent greenhouse gas. Compost of crop waste can reduce significantly methane emissions and reduce the need for chemical fertilizers (Ayilara *et al*., 2020). The majority of organic waste from agricultural crops can be converted by microorganisms into biofuels providing valuable renewable energy sources (Hnain *et al*., 2012). The anaerobic digestion is an efficient way of managing crop residues in an environmentally friendly manner resulting in high calorific methane gas (Sukhesh and Rao, 2018).

If control and treatment measures are not taken for horticultural biomass waste, the capture of CO_2 through photosynthesis will have no contribution to the reduction of atmospheric concentration. Due to the short period of development of horticultural crops (usually between 5 and 10 months) the sequestration of CO_2 in plants is not significant. If the crop waste is not reused in some useful way, their natural degradation by microbial decomposition produces the return of CO_2 absorbed by photosynthesis back into the atmosphere or the emission of methane (with a global warming potential 28-34 times that of CO_2). It is therefore essential to carry out policies for the systematic collection and valuation of greenhouse plant waste. Despite the high recovery potential of crop waste from greenhouse no integrated management system exists in the province of Almeria (Duque-Acevedo *et al*., 2020).

The research group of the University of Almería has strong existing networks that include Spanish level government policy makers (as the National Institute of Agricultural and Food Research and Technology – INIA and the Institute for the Diversification and Saving of Energy - IDAE), farmer groups and industry sectors all of whom have an interest in progressing innovative governance systems to support sustainable agriculture.

6. How was this research relevant to:

- The objectives of the CRP?
- The CRP research theme?

The research developed in the fellowship aligns with the theme "*Transformational technologies and innovation*" as it aims on progress in the knowledge of contribution of new technologies applied in greenhouse climate control to the improvement of horticultural crop production. Furthermore, the proposal is focused on the use of "*Digital Technologies*" as Computational Fluid Dynamics that allow to study the spatial distribution of climatic variables as air temperature, humidity, velocity and CO_2 concentration. This information can help growers to improve the climatic control of the greenhouses and reduce the use of inputs as water or pesticides.

The proposal also aligns with the requirements of "*Integrated Agricultural Production Systems*" under the theme "*Managing Natural Capital*" as it aims on progress a sustainable agricultural utilisation of natural resources such as solar radiation (improving cover transmittance), wind as driving force of natural ventilation and atmospheric CO_2.

The final goal of the project developed during the fellowship was to contribute to the knowledge of the carbon sequestration in intensive agriculture, a work line proposed by the Co-operative Research Programme.

7. Satisfaction

- Did your fellowship conform to your expectations?
- Will the OECD Co-operative Research Programme fellowship increase directly or indirectly your career opportunities? Please specify.
- Did you encounter any practical problems?

- Please suggest any improvements in the Fellowship Programme.

From the practical point of view, the fellowship has been in accordance with my expectations. Since I had already made stays of several months in other research centres, I imagined well how it could be developed. On the other hand, before the fellowship, the world situation caused by the COVID-19 pandemic made its development unpredictable. The first week of the fellowship was the last of confinement in the Netherlands, so quickly the work could be developed in the facilities of Wageningen University. The start of the war in Ukraine caused difficulties for 4 or 5 days in the remote connection via the internet with the computer service of the University of Almeria through which I had access to the CFD program ANSYS-Fluent. Quickly the technical problems were solved so I was able to work normally during the rest of the fellowship.

From the human point of view, the fellowship has far exceeded my expectations. I had been in 2008 for a few days at Wageningen University and knew some researchers. However, the possibility of working integrated into the team has allowed me to see how they work efficiently and in a coordinated way in a very pleasant environment. Similarly, life in Wageningen has been very pleasant due to its tranquillity, the ease of performing the activities of daily living. The availability of bike way throughout the country has allowed me to move in comfort and certainly improved my health. The only downside to a stay in Wageningen may be the difficulty in finding accommodation. Thanks to the fact that I booked my accommodation well in advance, even before I knew if I had been granted the fellowship, and thanks to the adequate financial aid received from the OECD, in my case the accommodation has also been one of the good things and not a problem for me.

My participation in the program will not be a direct help in my professional career because I am in a very stable situation, with a permanent contract. In addition, I already meet the necessary requirements to be able to promote to the last step as a professor-researcher in Spain. However, the realization of research fellowships in international centres is valued positively for the granting of aid to my Department of Education, my Research Group and the University of Almeria itself, since part of the funding is variable depending on objectives.

8. Advertising the Co-operative Research Programme

- How did you learn about the Co-operative Research Programme?
- What would you suggest to make it more “visible”?
- Are there any issues you would like to record?

In my case I learned about the OECD aid programme through a co-worker to whom I told last year my intention to come to the Netherlands for a fellowship. My colleague received the information through the National Institute of Agricultural and Food Research and Technology (INIA) of Spain.

One way to make the programme more visible could be to send the information through international scientific organizations such as EurAgEng (European Society promoting the profession of Agricultural and Biosystems Engineering) or ISHS (International Society for Horticultural Science). If they sent an email to their associates with program information, it would be a quick access route for many potential candidates. For my part, this year I have insisted to the research service of my university to sent an email to all researchers and has advertised the OECD program on the institutional account on the social network LinkedIn of UAL.

9. References

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