PAVER

AIoT for Cascade Hydroponic Greenhouses with Solar Energy Harvesting and Water Regeneration System

D3.2-Field trial design proposal

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Abstract

The design of the field tests proposes the use of the cascade system technique to achieve a high-yield, efficient crop while maintaining integrated nutrient management that ensures a sustainable approach. First, a state of the art is deeply studied to analyze different approaches to achieve the desirable objectives. Later, an experimental setup is planned taking advantage of the facilities at the Experimental farm of the Technical University of Cartagena. Then, the plant material and the growing conditions in soilless cultivation, including harvesting, are defined. Thus, aspects such as the crop characteristics (growth stages, plant density, number of cuts), the nutrient solution (composition, fertilizers), the water used (pH and conductivity), the water-reuse system and the environmental conditions are examined. Moreover, the tools and methods for monitoring the performance of the test are defined. These include plant, climate and irrigation measurements as well as nutrient and water-use efficiency, along with the data collection equipment and measurement frequency for each one of the studied variables. Finally, the procedures for data processing and the criteria guiding the statistical analysis are clearly stablished.

1 State of the art

It is projected that the global population will reach approximately 9 billion by 2050, necessitating a 70% increase in agricultural production to meet the growing demand (Fogarassy et al., 2020). This situation leads to a decrease in agricultural land availability and an increase in global food demand. These tendencies will increase the pressure on global freshwater reservoirs, already affected by climate change, as well as on global food security, leading to a loss of biodiversity and the use of an excess mineral fertilization, which will affect the overall sustainability of current agricultural systems (Jaramillo and Destouni, 2015). Considering this challenge, it is necessary to shift from an economy heavily dependent on non-renewable resources to one focused on developing more efficient and resilient systems of crop production. Consequently, circular economy practices are gaining growing recognition for their role in advancing sustainable agriculture (Praveen et al., 2024; Islam and Zheng, 2025). Such practices aim to preserve resources and minimize waste generation and pollution. In this context, the European Commission (2020), through its Circular Economy Action Plan, introduced an integrated nutrient management strategy aimed at promoting the sustainable use of nutrients and fostering the development of markets for recovered nutrients.

In this complex context, some innovative plant production systems are gaining increasing popularity due to their potential to enhance circularity and resource efficiency, deliver ecosystem benefits, and contribute to climate change mitigation (Orsini et al., 2020). Among them, closed-loop soilless cultivation systems offer significant potential to enhance resource efficiency and advance circularity by implementing optimized nutrient-management strategies. Cascade cropping systems are a type of closed-loop soilless cultivation, in which use the effluent (drained water and nutrients) from the primary crop to irrigate a secondary crop. Because nutrients often reach high concentrations in leachates, raising the salinity of the water, selecting salt-tolerant crops is essential to ensure optimal system performance (Karatsivou et al., 2025). Edible halophytes, such as glasswort, are emerging as promising cash crops that can be grown with the effluents of the primary crop, closing nutrient cycles and preventing pollution (Giménez et al., 2024). These plants are suitable for cultivation in soilless floating systems, which is one of the most straightforward and cost-effective methods for cultivating leafy greens. Moreover, Gómez et al. (2023) showed that edible halophytes grown with the leachates of a primary crop, had higher leaf quality than that observed for standard nutrient solutions.

In soilless systems, peat is the substrate mostly used; however, its harvesting despoils ecologically important peat bog areas, releasing stored carbon and increasing global greenhouse gas emissions Gruda et al. (2019). Therefore, the search for organic materials that can be used as peat alternatives has become increasingly important. Compost from agricultural and from agri-food industry waste can be an alternative to peat in soilless culture systems, as far as its use can be considered as an environmentally friendly practice considering the circular economy. Depending on its composition, compost can be used exceptionally as a standalone substrate, although it is normally used as a growing media constituent, due to its chemical properties (high EC and pH). In addition, compost can be considered an important resource for the biofertilization and bio-stimulation of crops due to its nutritional elements, humic substances and hormone-like molecules secreted by microbes (De Corato, 2020). More recently, agroindustry compost derived from organic residues has been proposed as a peat alternative due to its lower environmental impact and beneficial traits—such as pathogen suppressiveness and biofertilizing or biostimulating effects (Giménez et al., 2020)—which can enhance crop yield and quality. We hypothesize that the beneficial traits present in the compost can be primarily taken up by the primary crop and subsequently transferred through the leachates used to irrigate the secondary crop, thereby enhancing its performance.

2 Objective

This deliverable aims to select a production approach and define the configuration of an experimental field test to achieve a high-yield, efficient crop while maintaining integrated nutrient management that ensures a sustainable approach. For this purpose, the cascade system technique is selected because it enables the recovery of drained water and nutrients from a donor crop to support the growth of a salt-tolerant species.

3 Materials and methods

3.1 Experimental setup

The experiment will be conducted in an unheated greenhouse covered with thermal polyethylene film with polycarbonate end walls, situated at the Agricultural Experimental Field Station of the Technical University of Cartagena (UPCT; lat. 37°41′ N; long. 0°57′ W). The greenhouse is gothic type, with a size of 15m X 10m and a ridge height of 6 m (Figure 1).

Figure 1: Exterior view (A) and interior view (B) of the greenhouse.

In the greenhouse, natural ventilation will be provided by a single roof vent placed along the upper part (Figure 1A). An automated ventilation system will open vents when it is sunny and warm to allow for air circulation and will close when it is cold to retain heat to create the perfect humidity and temperature conditions for the development of the crop. Ventilation vent will incorporate an anti-insect mesh designed to minimize insect entry into the greenhouse, thereby protecting crops and reducing the incidence of insect-transmitted viruses.

A movable climate screen will be placed at the upper part of the greenhouse, separating the growing space from the roof structure (Figure 1B). As normal operation, during the night it will be deployed to reduce heat loss, and during the day it will be rolled up to allow sunlight in for heating and plant growth. However, during the summer, the climate screen will be deployed during the day to reflect partially solar radiation, thereby reducing the temperature inside the greenhouse. It will be automatically run by means of a solar radiation sensor.

Plants will be grown in galvanized iron gutters of pyramidal trunk cross-section, whose dimensions are 1.0/0.15/0.12/0.11 m (length/upper width/lower width/height, respectively), filled with peat (P) or agro-industrial compost (C) (Figure 2A). Fourteen gutters will be installed per growing bed. Six beds, three per substrate, will be randomly distributed throughout the greenhouse (Figure 2B). Every gutter will be irrigated using a 1/2-inch drip tubing with in-line emitters of 2 l/h spaced every 20 cm (Figure 2A). At the bottom of the gutters, a metal mesh will be installed to allow proper drainage collection. To facilitate drainage, the gutters will be placed with a 2% slope. Drains will be collected in separate black tanks (one for compost treatment and one for peat treatment) throughout cultivation and disinfected using an ultraviolet system to be used later as a component of the nutrient solution for the secondary crop. An outline of the cascade cropping system to be used in this proposal is represented in the Figure 3.

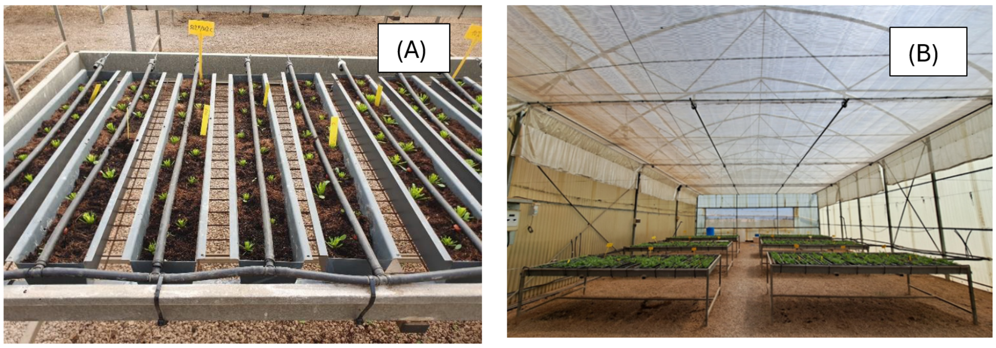

Figure 2: Layout of the gutters and the irrigation system (A) and layout of growing beds containing the gutters (B).

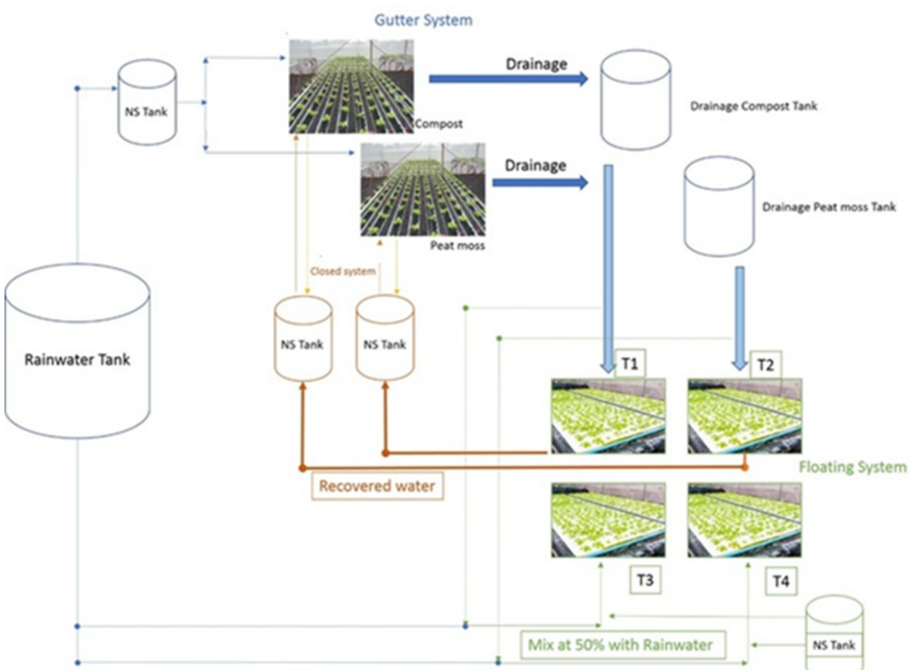

Figure 3: The experimental setup proposed for the cascade cropping system.

3.2 Plant material and growing conditions

As an example of hydroponic crops that can be cultivated in agrivoltaic greenhouses, in this proposal, wild rocket [Diplotaxis tenuifolia (L.) DC.] will be considered because it represents an innovative option for the industrial preparation of fashionable salads. This crop is involved in the variegated heritage of cultural and culinary traditions at the basis of the wealth of Mediterranean recipes. Seeds of cv. Tricia (Enza Zaden-Murcia, Spain) will be sown in Semirec® plastic trays measuring 63.2 x 31.5 cm (220 cells, cylindric cell volume 12 cm3). Trays will be filled with commercial peat-based substrate (Peat moss-Turbas y Coco Mar Menor, S.L., Spain) and will be placed in a germination chamber at 16 °C for two days. Then, the trays will be transferred to a greenhouse, where will be cultivated until plantlets reach the stage of four true leaves. The plantlets will then be transplanted into the previously described metallic gutters filled with either peat or an agro-industrial compost used as growing media. The peat is based on a Sphagnum peatmoss F315 mixed with a 60:40—blond: black proportion by volume, supplied by Turbas y Coco Mar Menor S.L. The dry-weight composition of compost consists of tomato and pepper juice waste (41%), leek waste (43%), and vineyard residues (16%). The characteristics of these growing media are presented in Table 1. Transplanting will be carried out at a spacing of 0.083 m within rows and 0.25 m between rows, resulting in a final planting density of 49 plants m-2.

Fertigation will be applied daily through an automated system. A nutrient solution (NS) optimized by the research team in previous projects (Egea-Gilabert et al., 2009), prepared with rainwater, will be used, in which we will equalize the nitrogen content for each substrate. The composition of the NS will be as follows: 8 mM NO_3^-, 2 mM NH_4^+, 2 mM $H_2PO_4^-$, 2.6 mM Ca^{2+}, 4.65 mM K^+, 1.12 mM Mg^{2+}, plus a commercial solution of microelement Nutromix 10, Biagro (2 mg L^{-1}) and Sequestrene (an iron chelate) (1.5 mg L^{-1}). The nutrient solution will be adjusted to 2.7 dS m^{-1} and pH 5.6. The concentration of the NS during the crop cycle will be half strength during the first week of plant growing and full strength from the second week to the end of the experiment. The solutions will be totally replaced every 28 days by new solutions with the same previous nutrient composition.

Irrigation will be applied daily with an automated system using soil moisture sensors (5TM; METER Group, Inc., Pullman, WA, USA). A percentage of the water holding capacity (WHC) will be allowed to decrease approximately 15% of the WHC. When the sensors detect this decreasing (a determined point in the volumetric water content (VWC)), 3 min of watering events will be applied in each growing medium, ensuring to reach the field capacity in both cases and a plus for a 15% of leaching fraction. Prior to starting the irrigation, the VWC of each growing medium will be estimated by measuring the voltage of the 5TM output, using a substrate-specific calibration equation according to Valdés et al. (2012).

Parameter	Peat	Compost
Physical characteristics		
Bulk density (g/cm^3)	0.5 ± 0.1	0.2 ± 0.0
Total pore space (%)	75.1 ± 0.1	87.6 ± 0.1
Air capacity (AC – %)	20.6 ± 1.2	32.7 ± 0.3
Water holding capacity (WHC – %)	57.0 ± 6.0	44.3 ± 5.0
Physico-chemical and chemical characteristics		
pH	5.3 ± 0.1	8.4 ± 0.1
EC (dS/m)	1.2 ± 0.1	1.6 ± 0.1
C/N	49.6 ± 0.1	9.7 ± 0.1
TOC (g/L)	233 ± 2.0	70 ± 1.0
Total N (g/L)	4.7 ± 2.6	7.2 ± 0.6
Organic N (g/L)	4.6 ± 0.6	7.0 ± 0.2
Nitric (mg/L)	4.5 ± 1.5	1.0 ± 0.4
Ammonium N (mg/L)	1.5 ± 0.1	0.4 ± 0.2
Total P (P_2O_5 g/L)	2.2 ± 0.1	15.3 ± 0.1
Available P (P_2O_5 g/L)	2.1 ± 0.1	6.2 ± 0.1
Total K (K_2O g/L)	1.6 ± 0.2	2.0 ± 0.1
Available K (K_2O g/L)	1.4 ± 0.1	0.8 ± 0.1
Ca (g/L)	9.0 ± 1.5	10.7 ± 0.2
Mg (g/L)	0.9 ± 0.3	0.16 ± 0.1
Fe (g/L)	0.6 ± 0.1	55.6 ± 0.1
B (mg/L)	0.2 ± 0.1	9.4 ± 0.1
Cu (mg/L)	2.8 ± 0.5	7.4 ± 0.2
Mn (mg/L)	35.5 ± 0.3	37.2 ± 1.4
Mo (mg/L)	0.8 ± 0.1	0.4 ± 0.1
Zn (mg/L)	7.2 ± 0.5	20.8 ± 0.5

3.3 Harvesting

Harvest will be carried out when the rocket plants reach the appropriated commercial stage (approximately 10 cm in height) to facilitate their subsequent processing as a minimally processed product. The cut will be made approximately three centimeters above the substrate to allow the plant to regrow. It is planned to carry out a total of five harvests during the crop cycle

3.4 Measurements

3.4.1 Plant measurements

Periodical and non-destructive measurements will be carried out during the growing cycle to monitor plant growth. Morphological and physiological parameters will be recorded at regular intervals to assess plant performance under the different substrates.

The measurements will be taken on the 10 plants chosen as samples on each replicate. The following parameters will be measured: plant height, SPAD index, dynamic leaf area and gas exchange parameters.

- Plant height. Plant height will be measured from the base of the stem to the upper edge of the canopy using a graduated ruler.

- SPAD Index. The SPAD index, an indicator of leaf chlorophyll content, will be determined using a portable meter Konica Minolta SPAD-502 Plus Chlorophyll meter (Konica Minolta Sensing, Inc. New Jersey, EE. UU.) Three readings will be taken on three young and representative leaves per plant, avoiding borders and leaf venations.

- Dynamic leaf area. Aerial photos of each replicate will be taken during the whole growing cycle. This permitted to visually follow the development of the canopy area. The pictures will be taken with a smartphone connected to a stick. The photos will be processed using the software ImageJ (NIH, Bethesda, USA), which permit to analyze the images by selecting only the green parts, corresponding to rocket plants, setting a scale based on a graduated ruler that will be positioned on the boards of each system, and measuring the effective aerial surface covered by the plants.

- Gas exchange parameters. To analyse the gas exchange parameters will be used an Infrared gas analyser (IRGA) portable photosynthetic system (LCi T, ADC BioScientific Ltd., UK). One plant per replication will be used to measure the gas exchange parameters. Measurements will be taken on fully expanded mature leaves from the apical canopy between 11:00 and 12:00h. Net photosynthetic rate (Pn), transpiration (E), intercellular CO_2 concentration (Ci) and stomal conductance (gs) will be measured at a reference CO_2 concentration of 400 µmol m^{-1} and a photosynthetic photon flux density (PPFD) of 800 µmol m^{-2} s^{-1}, under ambient temperature and relative humidity in the field.

During the cultivation, rocket leaves will be periodically harvested based on morphology and maturation. Destructive plant measurements will be carried out in every harvest. To enable both morphological and destructive analyses, four plants from each replicate (avoiding border plants) will be carefully uprooted, put in plastic bags and then collected in white polystyrene boxes. These plants will be used for morphological analyses such as:

- Plant height. Each plant is positioned on a graph paper and with the help of a graduated ruler the final value of height will be determined.

- Fresh biomass. After carefully washing the roots, the whole plant will be weighed using a digital scale, model PS 4500/C/2 (Radwag - Radom, Poland). Then the plant will be cut into two parts, shoot and root, and for both the weight will be determined, using the same digital scale.

- Leaf area. For a more precise determination a LI-3100C Leaf Area Meter (LICOR Biosciences Inc., NE, USA) will be used. This required detaching all the leaves for each single plant and positioning them on the machine's conveyor belt. An optical sensor positioned on the machine will be able to calculate the total leaf area (cm^2 $plant^{-1}$).

- Number of leaves. The number of leaves longer than 1 cm per plant will be counted.

- Root growth. Root length, area and volume, and the number of branches will be determined using a Winrhizo LA 1600 root counter (Regent Inc., Quebec, Canada) from pictures taken of each root system by a double-pass scanner incorporated in the counter.

- Plant dry weight. The dry weights (DW) of shoots and roots will be determined by drying in an oven at 60°C until constant weight.

The data collected from the previous analyses will be used to calculate other plant parameters:

- Yield ($kg\,m^{-2}$) will be determined by multiplying the fresh aerial biomass produced by the total number of plants within the cultivation area.

- Shoot-root ratio will be obtained by dividing shoot dry biomass by root dry biomass.

- Leaf-area ratio ($cm2\,g^{-1}$) will be determined by dividing total leaf area by total dry biomass.

- Specific-leaf area ($cm2\,g^{-1}$) will be obtained dividing total leaf area by shoot dry biomass.

- Relative growth rate (RGR) will be calculated for each harvest interval. RGR will be determined using the formula: RGR = ln (DW2/DW1)/time, where DW2 and DW1 represent the dry weights at the respective time points.

- Net assimilation rate (NAR) will be calculated as the rate of increase in its dry weight per unit of leaf area over a specific time. NAR will be determined using the formula: NAR = (DW2-DW1) (log L2-log L1)/time (L2-L1), where DW2 and DW1 and L2 y L1 represent the dry weights and leaf areas, respectively, at the respective time points.

3.4.2 Climate measurements

Greenhouse air temperature and relative humidity will be measured at 2.0 m above ground with an air temperature and relative humidity probe EE181-L (Campbell Scientific, Inc., Logan, UT, USA). A full-spectrum quantum sensor CS310 (Campbell 141 Scientific, Inc., Logan, UT, USA) with a photosynthetically active radiation (PAR) range of 389–692 nm will be used to measure photosynthetic photon flux density (PPFD) at a height of 2.0 m above the ground. Daily Light Integral (DLI) will be calculated as the total amount of photosynthetically active radiation (PAR) that a plant receives in a single day. It is expressed as micro moles of light per square meter per day ($\mu\mathrm{mol\,m^{-2}\,d^{-1}}$). For each growing period, DLI received by the crop will be calculated. The CO_2 concentration will be continuously monitored through an infrared gas analyzer (IRGA) (GMD20; Vaisala, Helsinki, Finlandia).

A CR1000 data logger (Campbell Scientific, Inc., Logan, UT, USA). will be used to register climatic data by connecting various sensors to measure the different environmental parameters. The data logger will be programmed to take measurements from connected sensors at set intervals. Before starting the experiment, all the probes used will be calibrated.

3.4.3 Irrigation measurements. Nutrient and water efficiency

The total amount of NS applied will be measured with volumetric counters. NS consumption is calculated as the difference between the input (volume supplied to the system) and output (volume left in the system at the end of the crop cycle). In addition, volumetric water content and temperature in the substrates will be measured by soil moisture sensors (5TM; METER Group, Inc., Pullman, WA, USA). Substrate solution pH and EC will be monitored using the PourThru method (Torres et al., 2010). pH and EC will be determined by a LAQUAtwin pH meter and conductivity meter (Horiba, Ltd., Kyoto, Japan).

The leachates of each growing medium will be collected in separate tanks and measured. The resulting chemical composition of the leachates will be analysed in terms of EC and pH and N (as NO_3^- and NH_4^+), K^+, Ca^{2+}, Mg^{2+}, Na^+, Cl^-. Ion concentrations will be determined by ion chromatography using a Metrosep A SUPP 5 column (Metrohm AG, Zofingen, Switzerland) at a flow rate of 0.7 mL $\mathrm{min^{-1}}$ for anions and a Metrosep C 2-250 column at a flow rate of 1.0 mL $\mathrm{min^{-1}}$ for cations, following the manufacturer's instructions.

The total irrigation volume will be determined to evaluate Water Use Efficiency (WUE). WUE (kg $\mathrm{m^{-3}}$) is calculated as a ratio between yield (kg $\mathrm{m^{-2}}$) and NS consumption per square meter ($\mathrm{m^3\ m^{-2}}$) (Howell, 2001).

Additionally, the amount of the nutrients drained and uptaken per plant will be quantified to determine the Nutrient Use Efficiency (NUE) for each nutrient. Specifically, the nitrogen use efficiency (NUE) will be calculated as the ratio between the crop yield and the nitrogen removed by the plants (kg $\mathrm{g^{-1}}$).

3.5 Data processing and statistical analysis

All statistical analyses will be conducted in R Studio (Version 4.2.2), and graphical presentations will be created using Microsoft Excel (version 2108). Data that will be normally distributed and homogeneous will be analyzed using one-way ANOVA, followed by Tukey's post hoc test at a 5% significance level. For data not fulfilling the assumption of normality, data transformations will be applied with the orderNorm function from the best Normalize package to achieve normalization. This approach will be applied to plant and irrigation measurements. For data that do not meet the assumption of homogeneity of variances, Welch's ANOVA will be used instead, followed by Games–Howell post hoc comparisons, also at a 5% significance level.

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