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Carbon capture from biomass flue gases for CO_2 enrichment in greenhouses

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ABSTRACT

Heating and CO_2 enrichment systems can improve yields in intensive greenhouse agriculture Combining both techniques, which are currently applied commercially, can potentially enhance their effect. The CO_2 must be separated from the other noxious gases present (such as CO, NO_X, and SO_2) to avoid them becoming part of the supply. The CO_2 is then provided to the greenhouse on demand in the same way as the heating. In this work, we show that an improved food productivity of a pilot-scale greenhouse system combined with CO_2 capture by adsorption using activated carbon and heating with alternative fuel. The proposed system's overall performance was evaluated and optimized. The best values were 46.7 g/kg of CO_2 storage capacity on the adsorbent bed, 99.99 % removal rate harmful gases from the gas supplied to the greenhouse, CO_2 levels of 1851.0 ± 262.8 mg/Nm^3 of the CO_2 levels in the greenhouse, and an enrichment time of 2.18 ± 0.92 h/day. The system's effective performance over extended periods (November–February) was confirmed and the productivity of a crop species (tomato) was compared to a control, showing an increment of 18 %. The results indicate that this is a valuable option for increasing the crop yield. By integrating this combined system with advanced climate control strategies, it is possible to maximize the CO_2 provided per day, leading to higher yields. The system proved to be stable under real pilot-scale conditions over winter periods (four months).

1. Introduction

Agriculture is one of the most important economic activities in the southeast of Spain. Fruiting vegetables are the main crops grown here, primarily in greenhouses under plastic. The utilization of various intensive agricultural techniques has allowed productivity to increase significantly. The average productivity increases for watermelon, melon, zucchini, tomato, and pepper have been 9.2, 6.7, 34.5, 46.8, and 68.2 %, respectively [1], when comparing indoor and outdoor cultivation. The increments relate to values obtained both inside greenhouses and outdoors. These crops are the most significant (in terms of production) in this part of Spain [1,2]. Improvements have recently been made to cultivation methods that can increase the productivity even more. Among these strategies are

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heating and CO_2 enrichment.

The general idea of advanced climate control is to prevent the temperature from falling below critical values, ranging 10–14 °C [3–6] below which the plants can suffer temporary or even permanent damage and subsequent decrease in productivity. This heating strategy is currently applied in relatively sophisticated but still commercial settings and has been studied in previous works [7–10]. Over last decade, fluctuations in fossil fuel prices have increased the need to look for alternative systems; this has allowed biomass heating to become an economically viable option, also because it is a resource that is available around the world [11–16]. One alternative is to use the biomass from the same plants; grown and pruned in one season and then used as the energy source in the following one [17,18]. This possibility has been studied in previous work [19], which showed that costs related to fuel consumption can be reduced even more. Nevertheless, adequate combustion technology needs to be implemented to overcome the problems associated with this fuel type, namely ash, moisture and chlorine [20,21].

Regarding CO_2 enrichment, the C3 group comprises the central area of fruiting vegetable plants (relating to their photosynthetic metabolism). Their metabolic route efficiency increases with the CO_2 concentration available in their surrounding environment whereas the opposite occurs when the concentrations falls below the atmospheric value [22]. Supplementing CO_2 is also advantageous in other similar applications such as aquiculture [23–25]. The source can be purified CO_2 or CO_2 from fuel combustion; however, the latter alternative also generates CO, SO_2, NO_X, ethylene, volatile organic compounds, ash, unburnt particles, and HCl, as is the case with solid biomass [26–28]. These undesirable compounds can be harmful to crops, leading to a decrease in productivity [29–34]. Previous works a reviewed CO, SO_2 and NO_X emissions from various biomass sources and evaluated various combustion devices [35, 36]. Injecting these flue gases without pretreatment would elevate the levels of these noxious gases inside the greenhouse environment resulting in the problems mentioned above. The values recorded in these works ranged between 3.7 and 26029, 1.0–1848, and 0.2–344 mg/Nm^3 (normal conditions, 0 % O_2) for CO, NO_X and SO_2, respectively. One way to avoid these compounds being present in the supply is to use activated carbon as a prior CO_2-capture step. This allows one to selectively adsorb the CO_2, by filtering out the other harmful compounds [37–39]. Van de Walls iterations are related to this selectivity [40] and the present work tests such an option.

To optimize production, the CO_2 concentration needs to be integrated with optimal temperature control during daylight hours. The most usual and cost-effective method to control the maximum temperature is by natural convection (opening the greenhouse windows) [41]. CO_2 enrichment can be performed even with partial aeration and still be beneficial [12,42] although the optimal approach would be to perform enrichment with the windows closed [12,42]. Various cooling strategies can be implemented to avoid air exchange with the outside environment [41,43,44]; these include fogging systems [45], mobile shading [45], and conventional air-conditioning equipment, although the latter involves a high electrical energy demand. Consequently, it would be desirable to integrate these strategies with renewable energy systems (e.g., solar energy). For this reason, combining a heating and CO_2 enrichment system is proposed, which reduces energy costs and environmental impact through the reuse of the vegetal waste generated in the greenhouse.

Our previous works on heating and CO_2 enrichment were carried out using the same pilot greenhouse system [35,46,47] but looking only at short periods hours. They laid the groundwork, providing a first step towards the experimentation carried out in the present work. The objective of this work is to demonstrate the technical stability of a combined heating and CO_2 enrichment pilot system over long winter periods (4 months) using biomass generated in the greenhouse. In addition, we will evaluate the crop yield, CO_2 storage capacity and the filtration performance of the activated carbon bed.

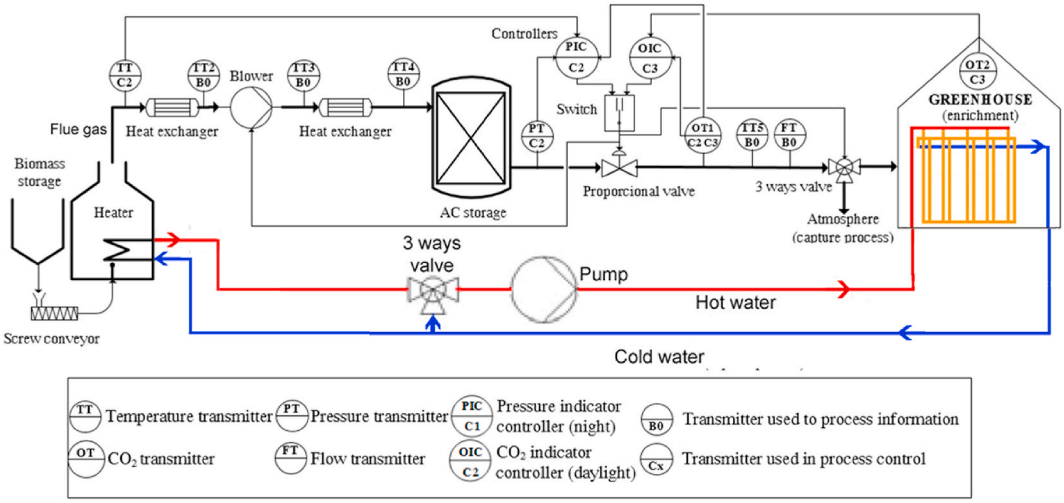

Fig. 1. Flow diagram and control strategy of the system tested for heating and CO_2 capture, and enrichment.

2. Material and methods

2.1. Plants and growing conditions

Solanum Lycopersicum (tomato) was used as the fruiting vegetable species cultivated in these assays. The plants were grown inside an 877 m^2 multi-span type ("Parral-type") greenhouse covered with polyethylene. Five hundred plants were grown in the greenhouse (10 lines, with 50 plants per line). Automatic windows were employed to control the maximum temperature; these were opened when a set point was exceeded (above 24 °C). Thus, the cooling strategy consisted of passive heat transfer by air exchange to the outside environment. The temperature was also maintained above a critical minimum value (12 °C) with using heating.

Concerning the heating strategy, the design focuses on integrating the control of the minimum temperature, CO_2 enrichment and CO_2 capture whenever heating is required. Another possible strategy would be to perform combustion to generate CO_2, in our case, this approach was not used. The periods when on-demand heating was required were usually at night; hence, the CO_2 generated from this heating was captured and made available for enrichment the following day. CO_2 enrichment was not performed when the inside temperature needed to be reduced (when exceeding the maximum setpoint value), this strategy was employed because enrichment is not cost-effective with the windows open. The radiation on the crops is another condition governing CO_2 enrichment effectiveness; therefore, this operation was only performed during the daytime. Regarding the climatic conditions, the weekly averages were measured for 1) the minimum temperature outside the greenhouse, 2) the temperature increase between the greenhouse's interior and exterior, and 3) the time of the minimum values.

2.2. Heating and CO_2 capture-enrichment systems

The system diagram is shown in Fig. 1 and includes two different sections: (i) the heating and (ii) the CO_2 capture for subsequent enrichment. A biomass boiler (Missouri 150000 with a 160.46 kW thermal output) supplied the system's thermal heat by increasing that increased the water temperature inside the water tank. From there, a "hot" water stream was sent around through a circuit. This stream was recirculated, with the heat being indirectly transferred over the entire greenhouse area. The circuit was constructed out of a combination of steel and polyethylene pipes. These were placed close to the soil surface (5 cm above). The solid fuel used was pine pellets, which have been previously characterized [19,48].

The CO_2 capture was performed using an activated carbon bed. The captured CO_2 was then supplied to the greenhouse. The flue gases generated in the biomass boiler were extracted from the chimney and compressed with a blower up to $20 \cdot 10^5$ Pa. The compressed gas passes through the activated carbon bed, which retain the CO_2 while other gases pass out of the bed. The system automatically operated with a proportional valve, which is located at the CO_2 tank outlet. This valve automatically controls the pressure inside the tank using a feedback control loop. The above-mentioned blower was automatically activated during this process to maintain the required pressure. The system has a three-way valve after the proportional valve which makes it possible to select where the gases are released (into the greenhouse or out to the exterior environment). The noxious species can therefore be filtered out of the stream during the capture process, thus removing them from the CO_2 enrichment supply. The capture process was performed whenever the activated carbon bed was not saturated with CO_2 (below 80 % capacity) and when combustion was required to supply energy for heating.

Regarding CO_2 enrichment, at the end of the CO_2 capture process the pressure in the tank was held at the working value mentioned before ($20 \cdot 10^5$ Pa). Since this value is higher than the atmospheric pressure, the gas stored in this tank will flow because of the pressure difference. This carried out when enrichment is required. Nevertheless, some of the CO_2 captured in the activated carbon bed remained after the tank pressure dropped to the atmospheric level. This might be because a certain portion of the captured CO_2 desorbed from the active granules after this first pressure switch but remained in the empty spaces between these granules and the tank volume not filled with the activated carbon bed. Regardless of the reason for the system's behavior, it was necessary to perform several pressure switches to pull out the rest of the stored CO_2. The blower was activated intermittently to carry out these switches maintaining a certain minimum pressure and managing the rest of the CO_2 being extracted. This extraction was stopped after reaching the 80 % saturation value mentioned above. Despite this, some CO_2 still remained in the tank but, for economic reasons. we considered it better to stop the extraction and thus, the CO_2 enrichment beyond this value. At the same time, the saturation level in the adsorption bed was monitored by measuring the CO_2 levels. In the first moments after starting the capture, the gas stream flowed out of the tank. The maximum amount of CO_2 that the carbon activated bed could retain was also checked experimentally by mass balance (Equation 9).

Conversely, the strategy followed to ensure optimal system performance focused on controlling the minimum temperature inside the greenhouse. Hence, the philosophy of the system performance was to prioritize the minimum temperature control.

2.3. Control strategy

The control structure is illustrated in the flow diagram, in Fig. 1. The system comprised various sensors and actuators. The variables controlled in the greenhouse were the CO_2 and temperature. These included the temperature in the outer environment and at different critical points around the system (the streams exiting the boiler, the blower, and the corresponding heat exchangers after these two units); and the CO_2 concentration in the outer environment and in the stream coming out the tank. In addition, the temperature at the water circuit was monitored at different points: after the boiler, at the three-way valve, and at the end of the water circuit (just before the three-way valve).There were various actuators in this system: the biomass boiler itself, the blower, the three-way valve placed between the CO_2 tank and the greenhouse (for the gasses stream), the proportional valve located before the CO_2 tank (for the gasses stream), the three-way valve placed after the biomass boiler (for the water stream), and the greenhouse windows (for control the maximum temperature). The control program was implemented using a licensed version of LabView® software.

Regarding the temperature control, a minimum value was maintained inside the greenhouse throughout the day and night. The setpoint value was 10 °C. Usually, this minimum value was not reached during the daytime. Two hours before sunrise (from 6:30 to 8:30 a.m.), the setpoint was increased to 12 °C to try to stimulate the plants metabolism and getting them ready to photosynthesize as soon as there was enough irradiance. Concerning the CO_2 control, CO_2 was injected on demand whenever level dropped below the minimum setpoint in the greenhouse environment a value of 700 ppm. To evaluate those moments when CO_2 injection was recommendable variables such as the CO_2 concentration, light irradiance and the temperature inside the greenhouse were considered.

2.4. Heating and CO_2 enrichment experiments

All the data concerning to the growing conditions were recorded throughout the experiment. The temperature and CO_2 concentrations inside and outside the greenhouse were among the variables recorded. Moreover, various information was extracted or estimated from the data overall. The complete list of equations and calculated parameters are included in the annex. In summary, Equation 1 and Equation 2 were used to calculate the thermal gradients in the system. Equation 7 and Equation 8 were used to calculate the CO_2 transference and losses. Both losses and increments can be considered, depending on the CO_2 concentration gradient (positive: an increase in the CO_2 concentration; negative: CO_2 transference). This gradient is the difference in concentration between the greenhouse interior and the outside environment. Conversely, Equation 9 was used to estimate the CO_2 captured after biomass combustion. This quantification was performed to corroborate the estimated values for the amounts injected. It also provides a more complete picture regarding the adequacy of the system's total adsorption capacity. The amount of CO_2 stored in the activated carbon bed was quantified by considering the concentration gradient of the gasses entering and exiting the tank during the capture process. Theoretically, the amounts injected should equal and exiting, and captured. Nevertheless, in the short term (a few days) these amounts can differ depending on the climatic conditions.

The aim was to estimate the total amount of CO_2 that the activated carbon bed adsorb. For this, certain specific experiments were performed. The system was management following a special procedure to maximize the time that CO_2 capture could take place. The process started during the first hour of daylight. As, the water circuit was cold from the previous night, it was left for a least 2 h before starting the experiments and the highest value possible was set for the boiler's water deposit (80 °C). A higher temperature can be dangerous for two main reasons: the first is that the recommended pressure levels inside the water tank can be exceeded and abrupt ebullition can take place; the second is that the maximum recommended value for the polyethylene pipes can be exceeded. The capture process was as long as possible. Despite these precautions, it was usual to have to interrupt this process because the water temperature in the boiler deposit reached its set point. If this was the case, the process was paused to let the water circuit temperature drop before starting the process again. For example, the water in the boiler deposit was replaced by cooler water (almost at the same temperature as the greenhouse interior) on the first occasion this happened. The procedure aimed to interrupt of the CO_2 capture as little as possible. The capture was performed until the saturation level was reached. This level was considered to have been reached when the CO_2 level of the gases exiting the tank was 80 % of those coming in.

The long-term experiments were conducted over the winter months (from December to January). However, the plants were transplanted into the greenhouse by September after being seeded two weeks previously. Over this period, the yield (fruits mass/cultivated surface) and the fruits number by surface were recorded. An identical crop was used as the control. This was grown in the greenhouse next to the one in which the heating and CO_2 enrichment were taking place. The same tomato variety was grown but without employing the two techniques. The same control strategy was followed regarding the other variables that influence growth. These included: the greenhouse design, the incident light reaching the crop, the watering rate and the nutrients supplied, the soil pH,

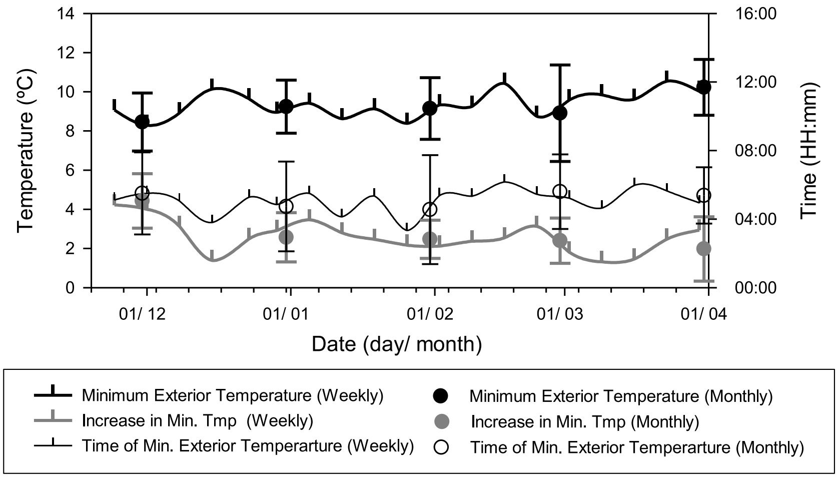

Fig. 2. 1) Minimum exterior temperatures, 2) the corresponding increase in the indoor greenhouse value, and 3) the time of day when this minimum was observed (for each day), and the corresponding monthly average.

and the salinity. A combination of both strategies should account for any possible difference in crop yield, namely: 1) controlling the minimum air temperature around the crop by means of heating, and 2) CO_2 enrichment to increase the concentration levels up to 1325 g/Nm^3 (700 ppm.).

3. Results & DISCUSSION

3.1. Heating and CO_2 capture

To evaluate the performance of the proposed technology it was run for several months (over the winter period). The climatic conditions considered important for plants growing during this period are the weekly averages for 1) the minimum temperature outside the greenhouse, 2) the temperature increase between the greenhouse interior and exterior, and 3) the time of the minimum values (Fig. 2). These values were analyzed because they determine the plant performance and thus their requirements (the supply of heating and, CO_2).

Concerning the performance of the heating and CO_2 enrichment system, data corresponding to the maximum temperature gradients between the greenhouse interior and exterior were plotted in Fig. 3. These gradients correspond to the periods when heating was provided according to needs. They are important to ensure an appropriate minimum temperature inside the greenhouse ambient. During this period when the minimum exterior temperature drops below the value for adequate plant growth, these gradients ensure that the plants do not present thermal stress responses.

The CO_2 capture and enrichment time (Fig. 4) are related to the heating demand although climatic conditions also have an influence factor such as wind speed, cloud cover, external temperature. Depending on these factors, it may be necessary to stop CO_2 enrichment during daylight hours, when it is normally applied. The usual heating demand was greater than the CO_2 enrichment. This trend is corroborated by the data presented in Fig. 4. This typical demand was in line with previous studies performed in this region [49,50]. This average fuel consumption overall was 36.7 ± 16.3 kg/h while the monthly maximum was 43.3 ± 22.6 kg/h (March). Concerning the heating and CO_2 capture time, the overall averages were 1.17 ± 1.16 h and 1.29 ± 0.70 h per day, respectively.

Regarding the performance of the CO_2 capture system, the data show that the activated carbon bed became saturated within 2.1 h (100 % saturated within 6 h). The global average for the experiment was 1.29 ± 0.70 h, value below the 80 % storage capacity. Concerning the average electrical energy consumption, this was 1.37 kWh during the capture process if one considers that the energy cost is 0.283 €/kWh (the average rate in Spain for 2023), the CO_2 capture costs amounted to 0.268 €/kg CO_2. This value depended significantly on the saturation level of the adsorption bed. For example, the CO_2 capture process cost 0.229 €/kg and 0.127 €/kg for adsorption yields of 80 % and 50 %, respectively.

For a detailed evaluation of the system performance, the average values were calculated (Fig. 5). The plotted data include: 1) the maximum CO_2 concentration achieved each day, 2) the weighted average concentration during enrichment periods, 3) the heating, 4) the CO_2 enrichment, and 5) the CO_2 capture times. The average maximum CO_2 concentration achieved each day was 1851.0 ± 262.8 mg/Nm^3 and the months with higher average CO_2 concentration values correspond to those with higher weighted averages. This was expected, considering that both variables relate to the amount of CO_2 supplied. Conversely, higher average monthly values correspond approximately to those months with lower outdoor temperatures. During these months, the periods when the ventilation system could be kept closed were shorter. The maximum interior temperature value above which the windows needed to be opened was reached sooner in the morning and later in the afternoon.

In addition, CO_2 enrichment was recorded the beginning and end of each day, along with the maximum concentration value per day, and the corresponding monthly averages (Fig. 6). These values mainly depended on two factors: light availability and outdoor temperature. The former changes according to the season of the year, whilst the latter depends on the climatic conditions - the lower

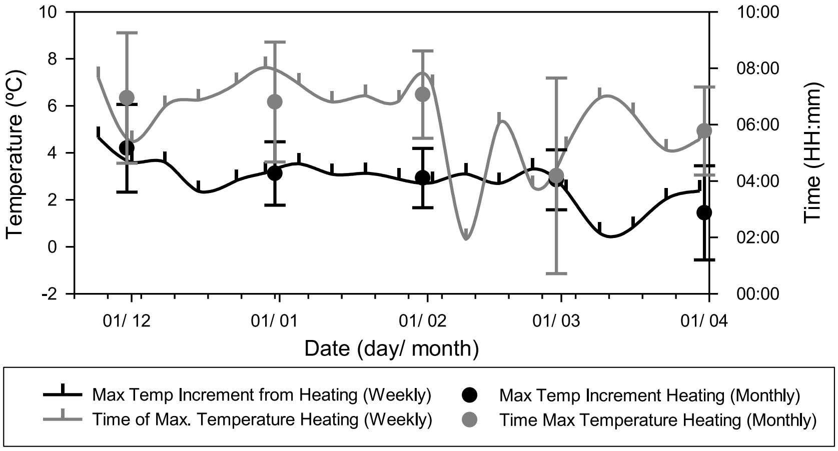

Fig. 3. Maximum temperature difference achieved between the inside and outside of the greenhouse, and the corresponding time of day (for each day), and the corresponding monthly average.

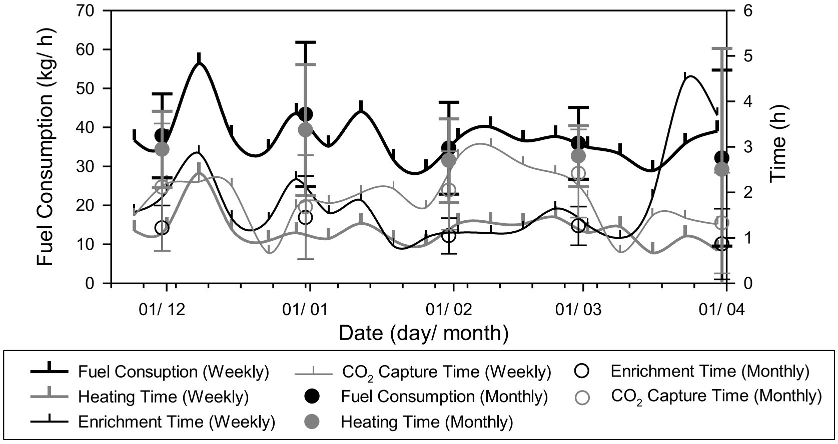

Fig. 4. 1) Fuel consumption, 2) time that heating was on-demand, 3) time when enrichment could be performed, and 4) time when CO_2 was captured from the flue gas generated each day, and the corresponding monthly average.

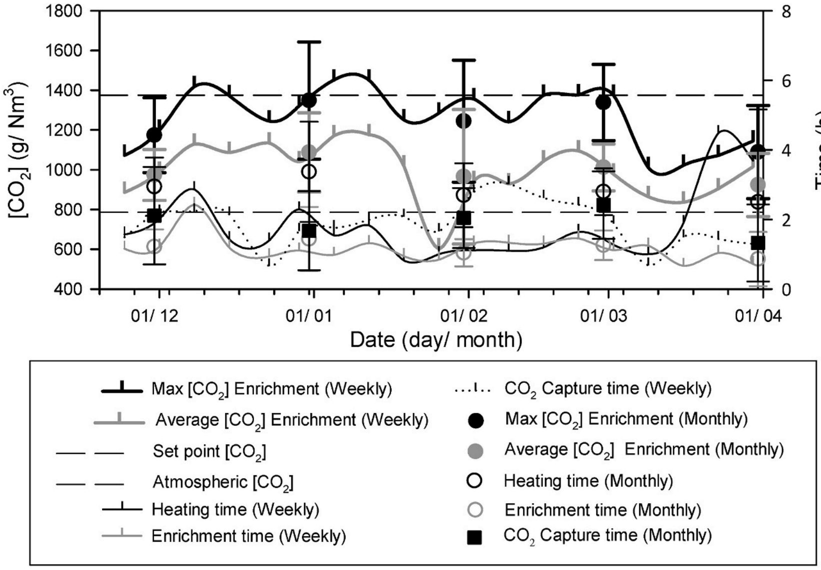

Fig. 5. 1) Maximum CO_2 concentration levels reached, 2) average CO_2 concentration when enrichment was performed, 3) the time when heating was on-demand, 4) enrichment, and 5) the time when CO_2 capture from the flue gas could be performed each day, and the corresponding monthly average.

the outdoor temperature, the longer the heating period required. Due to the climatic conditions CO_2 enrichment was only performed in the morning, while at other times, it performed before sunset. Thus, the average was around midday. Taking data as a whole, the usual CO_2 demand could be satisfied.

Some of the variables commented on above were recorded at different time intervals during the day. These variables were: 1) the average CO_2 concentration inside the greenhouse (Fig. 7), 2) the daily period during which CO_2 enrichment was performed (Fig. 8), and 3) the carbon capture time (Fig. 9). The daily average wind speed was also plotted to better understand the relationship between these three variables and air renovation (Fig. 10). These figures make it possible to study more accurately the influence between the climatic conditions and the controlled parameters (greenhouse temperature and CO_2 concentration). Such conditions change with the season and thus, so does the time during which CO_2 capture and enrichment are carried out.

The amounts of heat and CO_2 transferred to the greenhouse were quantified daily by means of mass and energy balances, making it possible to evaluate the heating performance. These balances have been detailed in previous research [35] and applied to the present work. The heat streams identified (Fig. 11. Equation 1, Equation 2, and Equation 6) were: 1) the transference from the water circuit, 2) the losses related to air exchange between the greenhouse and the outdoor environment (air renovation), and 3) heat accumulation. The estimations for the power input from the boiler were: 56.68 kW, 12.8 kg/h, and 15.88 MJ/kg for the heat transferred, the fuel input, and the calorific heating power, respectively. The average heat streams were 35.0 ± 33.2, 262.4 ± 235.0, and 458.2 ± 603.9

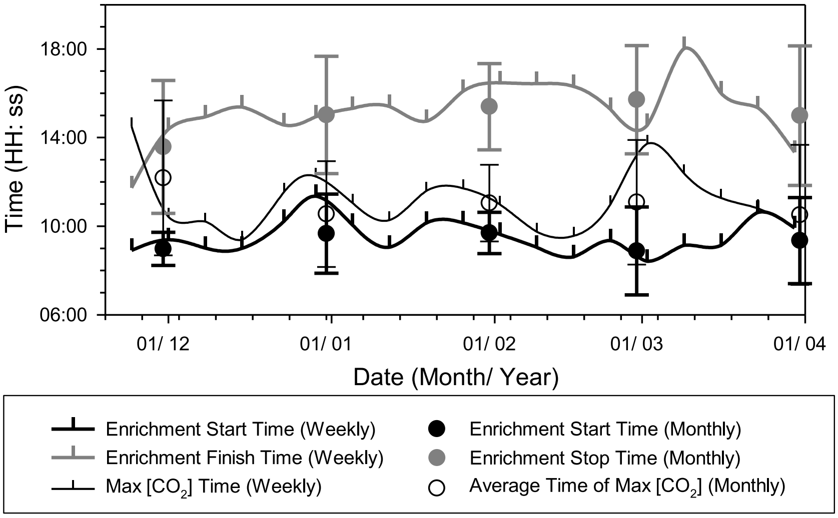

Fig. 6. 1) The time of day when enrichment was performed for the first time, 2) the time of day when enrichment stopped on the corresponding day, and 3) the maximum CO2 concentration observed each day, along with the corresponding monthly average.

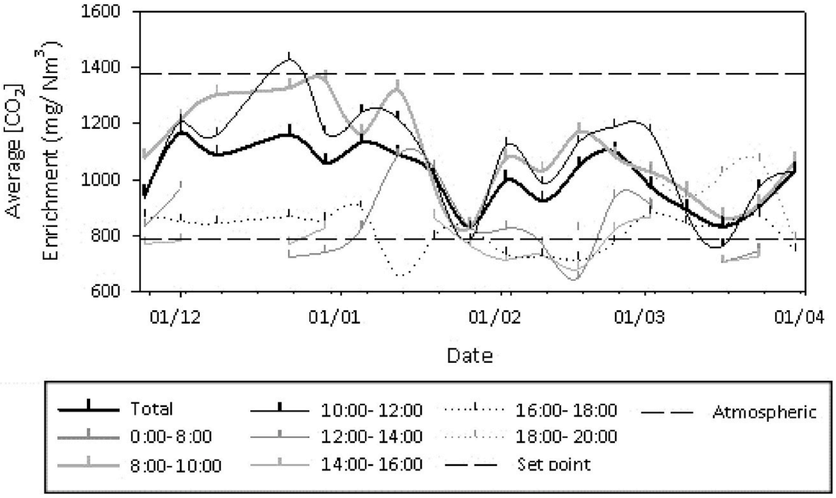

Fig. 7. Daily average [CO_2] during the enrichment periods. Average values calculated based on the time of day.

kW, respectively. Regarding the monthly averages, the values ranged from 21.84 (December) to 339.6 kW (March).

The estimated thermal losses and heat accumulation values were significantly higher than the transference from the water circuit. The accumulation's sensible heat was estimated considering the temperature decrease and the caudal flow. These values should be closer to the accumulation values. Nevertheless, the transference from the water circuit was of the same order of magnitude as the theoretical input power (35.0 ± 33.2 vs. 56.68 kW). The heat transmission efficiency could be estimated by focusing on the water circuit's heat transference and the theoretical biomass input power. At the same time, the standard deviation for each variable was relatively high. This might be a reason for the difference between the inlet and outlet heat streams. While the noise affecting these temperature values might also have an influence. Moreover, the heat transmission could be more important than initially. For example, the greenhouse substrate might act as a thermal accumulator, supplying or adsorbing thermal heat depending on the temperature gradient between the soil and the environment inside the greenhouse.

Throughout the experiment, the amounts of CO_2 injected and captured were quantified daily to obtain an overview of the process. There was some CO_2 loss due to air renovation and this amount was also quantified (Fig. 12). The mass balances (Equation 7 and Equation 8) allow us to determine the global averages of the CO_2 that is injected, captured and lost, the experimental values for these were 13.24 ± 7.94, 5.72 ± 4.57, and 2.40 ± 4.57 kg, respectively. The amount of CO_2 injected per day (i.e., the sum of CO_2 injected each month divided by the total days) ranged from 0.90 (January) to 17.9 kg (February). Regarding this difference, the CO_2 concentration of the gas stream pumped into the tank (from the boiler pipe or flue gases) was assumed to be stable for the corresponding balances. The CO_2 concentration in this stream was measured at three points as previously described, with the average being 6.3 ± 0.5

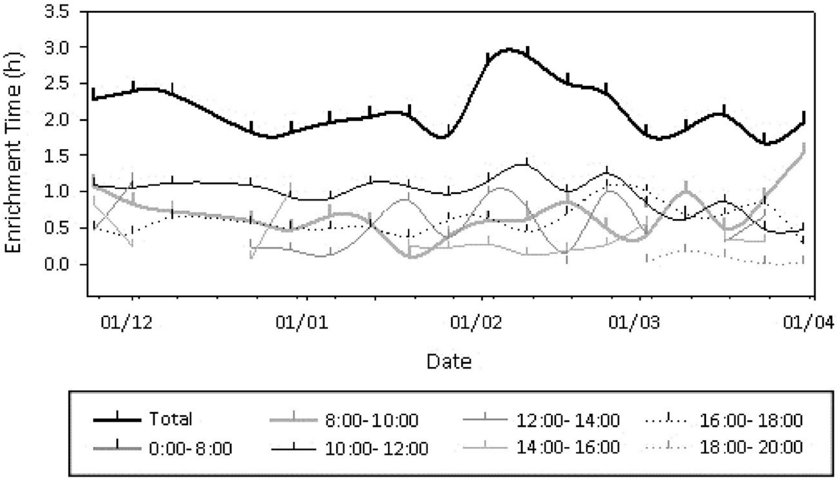

Fig. 8. CO_2 enrichment periods. Values calculated based on the time of day.

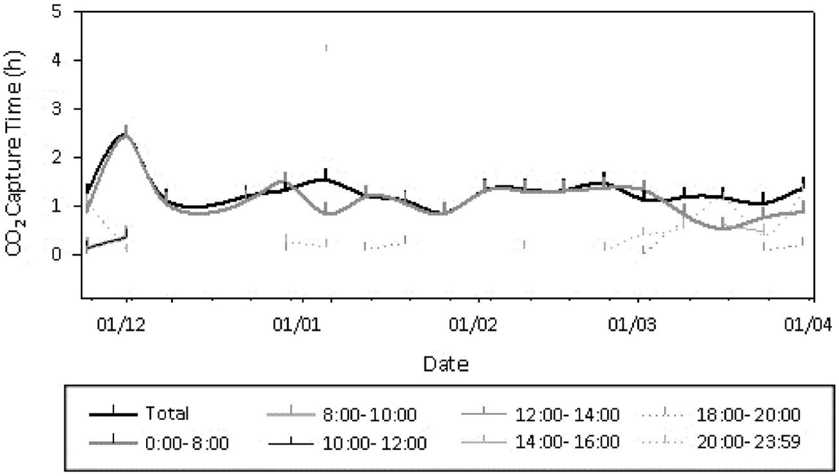

Fig. 9. CO_2 capture periods. Values calculated based on the time of day.

% vol.

Given the low standard deviation obtained, the above assumption was considered plausible. Nevertheless, an additional analysis was performed estimate this and the maximum CO_2 was identified for each day and then compared to the representative value; the higher of these two values for the corresponding calculations. This approach may lead to a certain underestimation of the amount of CO_2 captured despite these considerations. For example, the CO_2 concentration in this stream may vary even over the same day. During the initial design of this experiment, we did not foresee that this difference was going to be such relevant. A more precise quantification may require a continuous monitorization of this value during the entire experiment. For these reasons, the amounts of injected CO_2 should be regarded as the most reliable estimation. At the same time, despite this difference, the CO_2 amount lost due to air exchange (losses) was lower than that injected (and thus captured). Taking the total amount injected as a reference, up to 18 % was lost due to air exchange. Even though this value is high, it was possible to manage the CO_2 setpoint level.

The results obtained in this work highlight the importance of employing biomass in agricultural applications where heating may be required. With respect to CO_2 enrichment, employing carbon capture from flue gasses would be novelty application in agricultural greenhouse holdings. Currently, CO_2 enrichment is performed using pre-purified CO_2 or by burning fossil fuels such as methane. This technique allows one to further reduce CO_2 emissions firstly by fixing the CO_2 that is generated, and secondly by is partially capturing the CO_2 and reintroducing into the greenhouse environment. Therefore, some of this CO_2, is almost instantaneously re-fixed by other plants.

3.2. *Productivity*

The data on productivity (with or without CO_2 enrichment and heating) are plotted in Fig. 13. The productivity increased by 17.9

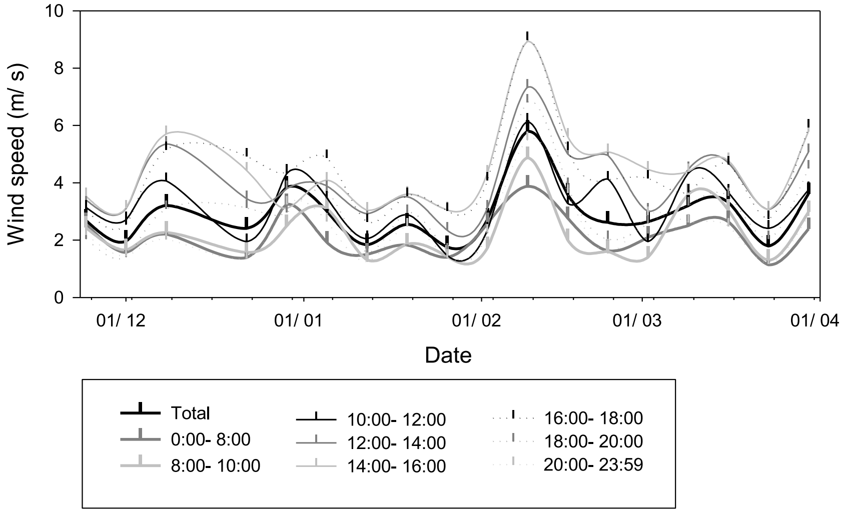

Fig. 10. Wind speed (daily averages) corresponding to the time of day.

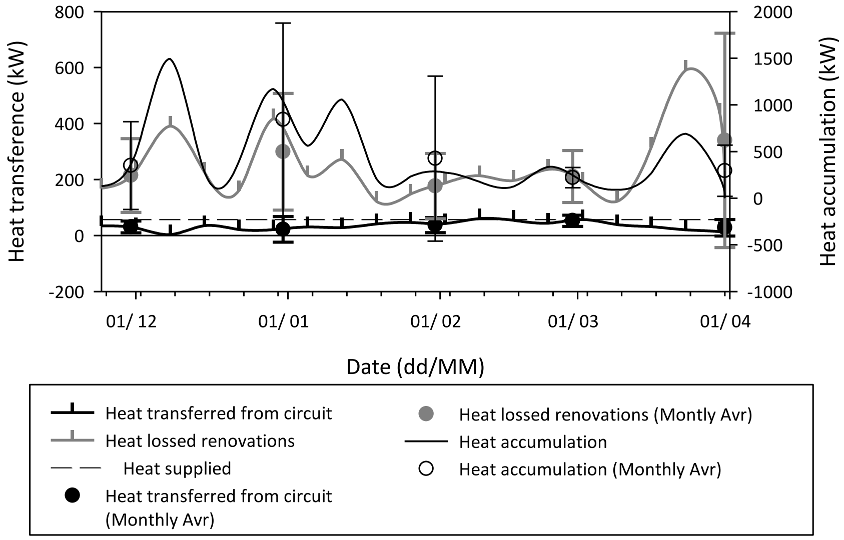

Fig. 11. Heat transference lost from the circuit due to air renovation inside the greenhouse, and heat accumulation.

%, and the mass per fruit was enhanced throughout the experiment. The maximum increase observed was 5.22 % in November, although this increment was consistently higher than 4 % up until February. Employing CO_2 enrichment with tomato crop could increase fruit productivity by 30–60 % [22]. Other authors have reported productivity increases from 8.6 % up to as high as 125.31 % [51]. However, it should be noted that our experiment was performed in a pilot-scale installation under real conditions. Regarding the number of fruits by surface area there was a slight increase in the greenhouse where heating and CO_2 enrichment were performed. This increase began some weeks before the productivity (mass/m^2). Hence, the fruits mass increased during this short period. After this point, the fruit mass became closer again since the number of the fruits began to increase along with the productivity. At the end of the experiment the increment was 9.5 % (comparing the number of the fruits by surface area in the greenhouse heating and CO_2 enrichment with that of the control). The maximum increment observed was 10.7 % on the 145th day (out of 174 days total; on, October 8, 2014).

Another important point is that the increase in fruit productivity is not directly related to the CO_2 concentration. Concentration values around the setpoint used (1375 mg/Nm^3) lead to higher photosynthesis rates and, consequently, a greater increase in the plants' vegetative mass, promoting a higher fruit yield. Another influencing factor is the CO_2 assimilation taking place in the plant canopy [52]. Some previous works have reported that exposing plants to high CO_2 concentrations lowers their CO_2 assimilation capacity. Hence, the positive effects of CO_2 enrichment can diminish over time [29,53]; this should not have occurred in our experiments. Under normal climatic conditions, it was usual to alternate between periods when enrichment was performed (with the greenhouse windows closed) or when it was necessary to open the greenhouse windows. When no enrichment was performed. Lastly, other properties might

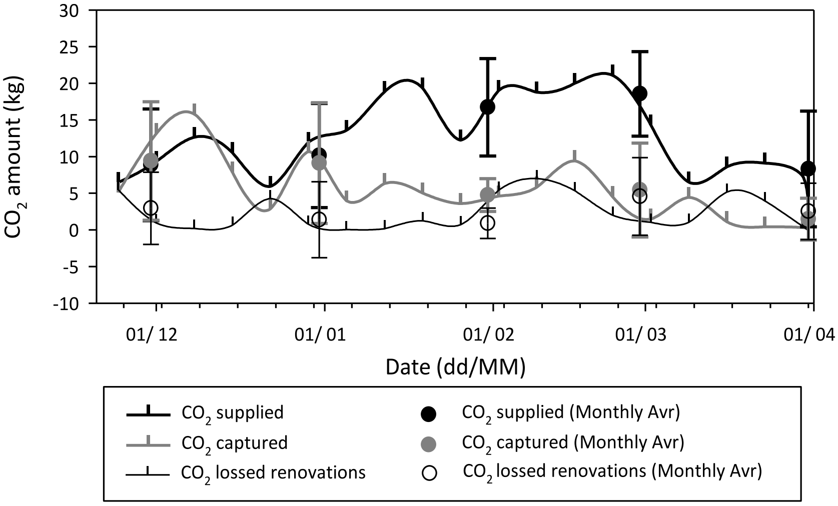

Fig. 12. CO_2 amounts supplied, captured, and lost due to air renovation.

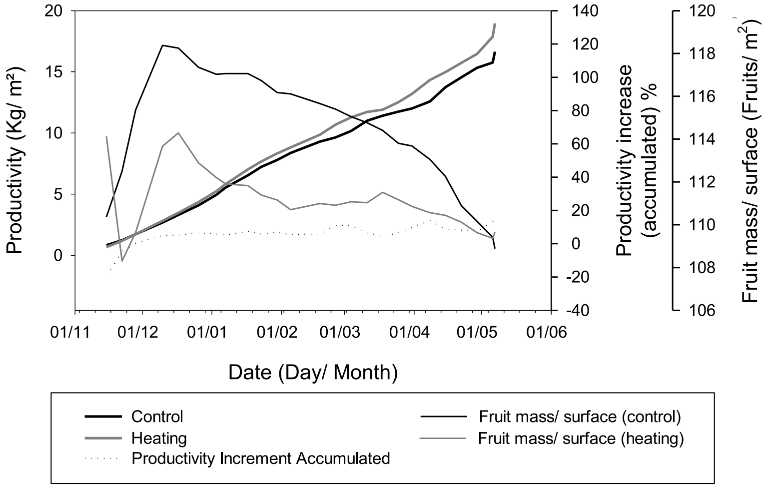

Fig. 13. Crop productivity comparation of greenhouses with and without heating, and CO_2 enrichment in the experimental greenhouse compared to the control greenhouse.

also have benefited, such as the fruit quality, in terms of uniformity (mass per fruit) and their organoleptic properties [51,54,55]. These could be the subject of further study.

The most significant increase in productivity was observed during the first months of the experiment (November & December), being which is important because these fruiting vegetables are usually less available at the beginning of the winter period; thus, they command a higher price. A subsequent increase in productivity was observed following this colder period, although, it was not as significant. Two distinct benefits can be obtained by combining these techniques, firstly, increased productivity, has been proven and second, the quality of the fruit produced, should also be considered. Further study is needed to assess quality indicators such as deformations or external imperfections, pest incidence, and the size and homogeneity of the fruit obtained.

4. Conclusions

This work has verified the performance combining two cultivation techniques in a real pilot plant-heating using solid biomass as an alternative fuel and CO_2 capture (generated by the same heating process) to provide CO_2 enrichment to the greenhouse. The process was evaluated over an extended winter period (November–February). The process was demonstrated to adequately remove the gases from the gas stream supplied (99.99 %) and to be applied to provide enrichment for a period of 2.18 ± 0,92 h/day. The average fuel each night could combusted generate enough CO_2 to meet the following day's enrichment requirements. Applying these two cultivation techniques together - heating and CO_2 enrichment – allowed us to increase the productivity of this tomato crops by up to 18 %.

The greatest, increase in productivity occurred in November (5.22 %). This is important because it can improve profitability a month that is the least productive during the growing season. Using the combined system also led to an increase in fruit quality during the winter (the coldest period) although this aspect requires further quantification. We propose that this could be a promising area for future research.

Equations

$$q' = \frac{V_{crt}\ c_{p\ H2O}\ \left(T_{H2O\_int} - T_{H2O\_fnl}\right)}{\Delta t}$$

Equation 1. Heat transferred from the water circuit.

T_{H2O_int}: initial water temperature. T_{H2O_fnl}: final water temperature. V_{crt}: water circuit volume. c_{pH2O}: water calorific capacity. Δt: time elapsed for the heat balance considered. q': heat transferred.

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$$q' = \dot{m}_{air}\ c_{p\ air}\ \left(T_{grn} - T_{env}\right)$$

Equation 2. Heat exchanged due to air renovation.

T_{grn}: greenhouse indoor temperature. T_{env}: environment temperature (outside the greenhouse). $\dot{m}$: mass velocity of air exchange (mass/time). c_{pair}: air calorific capacity.

$$\dot{m}_{air} = Renov \cdot \rho_{air}$$

Equation 3. Mass velocity (mass/time) of air renovation.

$\dot{m}_{air}$: air mass velocity (mass/time). *Renov*: air renovation exchange between the greenhouse and the environment (volume/time - estimated using Equation 5). ρ_{air}: air density (estimated using Equation 4).

$$\rho_{air} = \frac{P}{R_{spc}\ T_{grn}}$$

Equation 4. Air density as a function of pressure and temperature.

P: Pressure (this is usually the atmospheric pressure for points 8.2 and 8.3–101.125· 10^3 kPa). R_{spc}: specific constant for the gas considered, in this case, air: 287.058 J/(kg· K). ρ_{air}: air density.

$$Renov = (0.29\ v_{wind} + 0.76)\ V_{grn}\ R_{rnv}$$

Equation 5. Estimation of airflow exchanged by renovation between the greenhouse and the outside environment.

V_{wind}: wind velocity. V_{grn}: greenhouse volume. R_{rnv}: constant (0.907). v_{wind} and v_{grn} are expressed in m/s and m^3, respectively.

$$q' = V_{grn}\ c_{p\ air}\ \frac{\left(T_{grn\_fnl} - T_{grn\_int}\right)}{\Delta t}$$

Equation 6. Heat accumulated during the time considered.

Δt: time elapsed for the heat balance considered. $Tgrn\_fnl$: greenhouse indoor temperature at the end of the time interval considered. $Tgrn\_int$: temperature outside the greenhouse at the end of the time interval considered.

$$\dot{m}_{CO2\_iny} = \frac{[CO_2]_{tnk}\ q\ (P + P_{tnk})\ M.M.CO_2}{R\ T_{grn}}$$

Equation 7. CO_2 injected into the greenhouse. q: flow of the stream coming from the tank. P: pressure outside the tank (usually this is the atmospheric value). P_{tnk}: interior tank pressure.

$[CO_2]_{tnk}$: CO_2 concentration in the gas expelled from the tank. q: gas flow. P: pressure outside the tank under normal conditions (Again, this should be the atmospheric value). P_{tnk}: tank pressure. $M.M.CO_2$: CO_2 molecular mass. R: molar gasses constant. T_{grn}: greenhouse temperature. $\dot{m}_{CO2\_iny}$: mass velocity of injected CO_2.

$$\dot{m}_{CO2\_exc} = \frac{\left[[CO_2]_{grn} - [CO_2]_{env}\right]\ Renov\ P\ M.M.CO_2}{R\ T_{grn}}$$

Equation 8. CO_2 exchange due to air renovation.

$[CO_2]_{grn}$: CO_2 greenhouse concentration. $[CO_2]_{env}$: CO_2 environment concentration (outside the greenhouse). $\dot{m}_{CO2\_exc}$: linear mass velocity of injected CO_2 (mass CO_2/time). $\dot{m}_{CO2\_iny}$: mass of injected CO_2. The air renovation was estimated as indicated in Equation 5.

$$\dot{m}_{cpt} = \frac{\left[[CO_2]_{tnk} - [CO_2]_{fgss}\right] q\,(P + P_{tnk})\, M.M.CO_2}{R\,T_{grn}}$$

Equation 9. CO_2 captured from biomass combustion.
$[CO_2]gss$: CO_2 concentration in the gas entering the tank (thus, leaving the biomass boiler). $\dot{m}_{cpt}$: *mass flow of captured CO_2.*

CRediT authorship contribution statement

J.V. Reinoso Moreno: Conceptualization, Formal analysis, Investigation, Methodology, Writing - original draft. **M.G. Pinna-Hernández:** Conceptualization, Data curation, Investigation, Methodology, Resources, Supervision, Validation, Visualization, Writing - original draft, Writing - review & editing. **J.A. Sánchez Molina:** Conceptualization, Investigation, Validation. **M.D. Fernández Fernández:** Conceptualization, Investigation. **J.C. López Hernández:** Conceptualization, Investigation, Methodology. **F.G. Acién Fernández:** Conceptualization, Formal analysis, Investigation, Methodology, Supervision, Validation, Visualization, Writing - review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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