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Comparison of organic substrates in urban rooftop agriculture, towards improving crop production resilience to ~~water stress~~ tremporally drought in Mediterranean cities

Short running title: Comparison of organic substrates in urban rooftop agriculture resilience to water stress

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Abstract

BACKGROUND: Urban agriculture contributes to meeting the growing food production demand in cities. In the context of low water availability, it is important to consider alternatives that are able to maintain production. Through a circular economy vision, this study aimed to assess the use of substrates made from local materials as an alternative for urban agriculture in periods of low water availability, due to water supply cuts. The substrates used were coir commercial organic substrate, vegetable compost from urban organic waste, perlite commercial standard substrate, and a mixture of the urban compost and perlite (1:1) were used for 3 consecutive crop cycles of lettuce (*Lactuca sativa* L. var. crispa). The crop cycles were performed in the spring and summer periods of 2018 to observe the performance during warmer periods of the year in an integrated rooftop greenhouse near Barcelona. Each substrate was assessed under conventionally irrigation (0-5 kPa) and temporary water restricted conditions (irrigation stopped until the water tension reached -20 kPa perlite). RESULTS: In terms of yield, our results show that the compost and mixture were similar to those obtained from perlite (11.5% and 3.7% of more production in a restricted water condition). Organic substrates increased the crop's resilience to water restriction in contrast with the perlite. In particular, water lost took longer in coir (1 and 2 crop cycle); however, when dryness began, it occurred quickly. CONCLUSION: The vegetable compost and the substrate mixture presented tolerance to temporary water restriction when water restriction reached -20 kPa.

Keywords: Circular economy, sustainable cities, soilless system, water stress resilience, temporary water restriction, urban agriculture.

1. Introduction

Currently, the increase in population within cities has created a concern due to an increased demand for resources such as energy, water, and food. This situation is exacerbated by the advance of climate change Different problems have been foretold, among which it is worth mentioning extreme heatwaves, reduced water availability, the increase of relative humidity and, for concomitance the increment of pests and diseases[1]. In this way persistent droughts, are one of the biggest problems to be addressed in agriculture due to the high water demand of food production [2]. In this sense, it is required to develop strategies that allowing to maintain the food production.

Urban agriculture (UA) is an alternative to satisfy the increasing food demand, contributing to food production's sustainability by reducing different production chain elements, such as energy in distribution and used packaging [3]. UA can be carried out from different scales such as home to community gardens, with different degrees of sophistication such as the use of irrigation systems, special substrates, outdoor production or through greenhouses. Even on different levels of a building, both inside and outside, in this sense buildings integrated roof greenhouses contribute to sustainable and ~~F~~food ~~S~~security city strategies; where both circular economy and the use of food-energy-water approaches are used~~.~~[4]. The advantage of rooftop greenhouses is access to unutilized spaces, increasing current local food production, and reducing the environmental load associated with food production and the buildings that sustain it [5]. The evaluation of unoccupied roof spaces for greenhouse found that these are usually small and well-ventilated and have a very low relative humidity. This leads to a condition with high water consumption by plants and, therefore, a propensity for crops to suffer hydric stress [6].

Barcelona is an example of a Mediterranean city area, where droughts have been repeated cyclically for the past two decades. This situation has led to creating a management plan that aims to prioritize water uses in cities, especially during emergencies. UA is considered as a green space amenity activity rather than an agricultural activity in Spain, hampered by the legal restrictions applied to these areas. As an example, tap water irrigation of private gardens and city parks was forbidden during water shortages in 2008 [7]. This highlights the importance to develop alternatives to alleviate drought conditions of urban crop systems and maintain food production. There is a need to study strategies and technologies that allow the development of crops in water-limiting conditions, such as irrigation optimization, reuse of leachates, and soilless culture systems (SCS). SCS is frequently used to establish crops in an artificial medium to produce food under different growing conditions [8].

Within food production in the UA, the supply of water is essential for its development, water cuts can be generated by different reasons (electricity or water supply), this can negatively affect crop yield. It is necessary to generate strategies that mitigate the effect of low water availability and contribute positively to the production of food. Considering the above, it is desirable to use substrates that present characteristics such as a large amount of water retention, and it is available over time. In this sense, the use of substrates reduces the risk in a situation of water stress, in the event of a problem with electricity or water supply. It is understandable that, in the event of a very prolonged water cut, there is no guarantee that this will prevent the problem completely, and the reduction in performance will be strongly affected. The objective is to generate alternatives that mitigate the effect of low water availability, and the use of local organic substrates is one of these. A variety of organic and inorganic substrates could be suitable for crop production under restricted water availability in urban settings.

One of the most used substrates is perlite, an inorganic substrate characterized by its capacity for aeration, drainage, and optimum water retention. However, a high amount of energy is required for its production and transportation. Organic alternative substrates widely use include coir and compost [9]. These present desirable substrate characteristics, such as high water holding, cation exchange, that are comparable to perlite). Coir is an agricultural waste and, therefore, a renewable resource. However, it must be noted that coir is a material from a tropical crop produced in geographical areas far from maximum horticultural use and present the same perlite problem on transportation. Compost is an alternative to coir[10], since it is possible to obtain it locally, avoiding transportation. Compost can be produced from different local organic waste, such as domestic waste, municipal pruning, restaurant waste, among others, which is highly available at city levels. Its use as a substrate contributes to the recovery of organic waste resources and reduction of dependency on nonrenewable substrates, such as perlite. The recent increased interest in urban agricultural activities highlights the timely need to investigate low environmental impact substrates. Alternative urban organic substrates need to be easy to manage and available, financially feasible, have a low environmental impact, show high moisture retention, and have nutrients that are readily for produce high quality crops.[11].

Organic substrates have been widely studied for their use in the horticultural industry[12–14] but not in the UA circular economy context. There is an urge in both horticultural industry and gardening to study organic materials derived from agricultural, industrial, and municipal waste streams. The disposal of such organic (also referred to as biodegradable) waste materials is an environmental problem[15], and their reuse as substrates might provide a suitable solution[16]. Compost from municipal organic waste would specifically target reduction of urban organic waste to landfill and reuse, towards a short-chain circular economy and contributing to sustainable development goal (SDG) 11 (sustainable cities and communities) and SDG 2 (sustainable food production)[17] Considering a future scenario of low water availability, which can be addressed from the use of organic substrates, the need arises to study the behavior of these substrates under more restrictive conditions, in such a way, to generate strategies that allow maintaining food production in situations where the use of water is restricted in urban communities.

We hypothesize in a context of water scarcity, where the water supply can be affected temporary, it is essential to have local substrates, which avoid dramatic drops in crop yields. Within urban agriculture, the use of compost for food production is a viable alternative in terms of maintaining yield under conditions of reduced water, concerning conventional substrates such as perlite. The objectives are to determine the agronomic feasibility of using alternative substrates for perlite in an RTG in the context of UA and characterize the behavior of a green leaf crop as an indicator of the substrates' crop production performance under conventional and temporary restricted irrigation conditions

2. Materials and methods

2.1. Study site

The experiments were conducted in the rooftop greenhouse laboratory (i-RTG Lab), a cropping system representing other UA projects developed[18]. It is located in the Environmental Science and Technology (ICTA-UAB) building on the campus of the Universitat Autònoma de Barcelona. Protected cultivation is performed under a steel and polycarbonate greenhouse structure. The climate conditions in the i-RTG Lab were passively controlled.

2.2. Substrate characteristics

The study focused on three substrates. These consist of perlite as control substrate, coir, green compost, and a (1:1) mixture of the green compost and perlite. Substrate physical and chemical properties as shown in Table 1. Analytical methods and tables of the result are provided in the supplementary information section. The green compost used was derived from municipal pruning waste, which is chipped and mixed for 3-4 weeks and irrigated 4 times per month with rainwater (3 months of composting process in open-air piles). When the composting process is finished, the material is sieved to 10 mm and packed. The green compost used present a 57.9% of organic matter, an EC of 2.77 dS·m^{-1}, and a pH of 7.79.

2.3. Experimental design

The experiment consisted of monitoring substrates performance during three crop growing cycles between spring and summer of 2018 in order to include warmer seasonal periods. Internal and external meteorological conditions of the i-RTG were recorded (Datalogger model CR3000; Campbell Scientific Inc., USA), a summary of the information is given in Table 2.

The three crop cycles are considered independent (Table 3). The three substrates selected were tested under conventional irrigation (supplying all water requirements) and water temporary restricted conditions (cut the irrigation to reach -20 kPa) in triplicates during each three crop cycle, except perlite, which was tested in duplicates: two under conventional conditions and the other temporary water restricted conditions.

A 70 m^2 study area within the 125 m^2 i-RTG facility was used. Growing bags' dimensions were 0.4 m x1.0 m, and they had a volume of 0.04 m^{-3}.. Each plant was planted at distances of 0.2 m x 0.4 m resulting in 4 plants per substrate bag, three bags per row, and 0.5 meter distance between rows, as shown in Figure 1. UA uses low substrate volumes to reduce weight, infrastructure, and costs. Within this work, a proportion of 0.01 m3 of substrate per plant has been used, which is a high value compared to normal conditions. This relationship between the substrate plant-1 ratio was determined to avoid a fast shortage of water (in one or two days in the summer period). Oak leaf lettuces (*Lactuca sativa* L. var. crispa) seedlings were planted in the four substrates. Crop growth was monitored and growing conditions controlled, following conventional agronomic guidelines for lettuce production. During the growing periods, the diseases and deficiencies were monitored and controlled.

2.4. Irrigation management

The nutrition solution was provided to the lettuces via a drip fertigation system. The nutrient solution contained: HNO_3 0.063 g·k^{-1}, KPO_4H_2 0.136 g·k^{-1}, KNO_3 0.101 g·k^{-1}, K_2SO_4 0.174 g·k^{-1}, $Ca(NO_3)_2$ 0.164 g·k^{-1}, $CaCl_2$ 0.111 g·k^{-1}, $Mg(NO_3)_2$ 0.148 g·k^{-1}, and microelements 0.0001 g·k^{-1}.) Irrigation volumes were adapted and optimized to the needs of lettuces grown in the control substrate (perlite). They ranged between 0.0003-0.00045 m^3·day^{-1}plant^{-1}. Induced water restriction took place 20 days after transplanting to make a late temporary drought when the plants were fully developing and required a higher water and nutrient supply following the methodology proposed Kerbiriou *et al.* [19].
This temporary restriction was applied by completely stopping irrigation until the perlite bags reached -20 kPa. At this time, irrigation was reestablished for all the water restricted rows. Water tension in the susbtrate was determined with an analog 12 cm tensiometer (irrometer® MLT) through the hydric potential variation, with a range of 0 to -40 kPa.

Also, in the third crop cycle, a second temporary hydric restriction was performed. This second restriction consisted of the same irrigation stoppage, but it was only maintained until the tensiometers in the control substrate perlite reached -10 kPa.

2.5. Crop system monitoring conditions; irrigation data collection and substrate physicochemical analysis

To the water flow characterization, a daily sampling was performed in each repetition of the crop cycle, and the amount of irrigated water, the leachates drained, and its electrical conductivity was measured (Table 4). The physical characterization of the substrate was assessed with 2 randomly samples per row of each substrate (at the end n= 6 substrates per treatment and n = 4 for perlite control) evaluated bulk density, pore space or porosity, and dry matter and moisture content (Volumetric amount of water) at the start and end of the complete crop cycles by the ring method[20]. It was also shown the differential of the water content in each substrate between the conventional irrigation treatment and the restriction irrigation treatment (θ %W-θ %S).

2.6. Crop sampling

At time of harvest, plant fresh weight was determined (g of the commercial part of lettuce, as fresh yield, Table 5). For the sampling, five lettuces were taken randomly from different repetitions of each treatment (for each of the three rows of each treatment n= 15, except the control, which was two rows with n= 10 lettuce in total). At the end of the crop cycle, when the crop was harvested, the final yield was determined (g of the commercial part of lettuce, Table 5). The mature index used to cut the lettuce is based on head compactness. A compact head which can be compressed with moderate hand pressure is considered ideal maturity. A very loose head is immature and a very firm or hard head is overmature[21]

2.7. Statistical analysis

The crop measurements were expressed using average values and standard deviations. "R" version 3.1.2 software[22] was used to determine significant differences between the different substrates and the effect of temporary water restriction. The significance was tested using a one-way analysis of variance (ANOVA). Before the statistical analysis, the assumptions of ANOVA were checked by a Shapiro-Wilk (normal distribution) and Levene test (Vvariance homoscedasticity). Multiple comparisons of the means were determined by a post hoc Duncan test. When the data were not normally distributed or present variance heteroscedasticity, a Kruskal-Wallis test was used.

3. Results and Discussion

The commercial production and the crop development were analyzed, and a difference was detected between the lettuces in the different substrates by comparing the first tests to the second crop cycle. Within the third crop cycle, it was possible to appreciate a lower variability between the yields of plants irrigated conventionally and with temporary water restriction. In addition, a trend towards a reduction in yield, regarding on the applied water restriction (-10 and -20 kPa).

3.1. Substrate characteristics

At the end of the three consecutive experiments coir presented an 81.76% water content, the perlite showed a 14.43% water content, and the vegetable compost and substrate mixture showed 31.62% and 25.29% water content, respectively. The coir showed the lowest value for the BD, with 0.09 kg·m^{-3}, followed by perlite, mixture, and compost, the latter with 0.23 kg·m^{-3} (Table 4).

Perlite: In this study, it was not possible to see final compaction of this substrate, which was possible in all the other substrates as the compost, where it was possible to perceive a reduction in the volume and substrate inside the bag, being in the last crop cycle a denser material (Table 4). The leachates electrical conductivity in the conventional irrigation ranged between 0.86 dS·m^{-1} and 1.50 dS·m^{-1} depending on the percent drainage or the water consumption plants.

Coir: The amount of water at the end of the assay for the conventional irrigation coir was 71.17% (Table 4). Compared to the conventionally irrigated perlite (56.89%), there was a 14% higher WC in the coir. Additionally, the coir showed the smallest BD of all the substrate used in this assay, with 0.1 kg·m^{-3}. In other word present a very low weight and high water retention, characteristic desirable in a substrate. The electrical conductivity in coir treatment was constant throughout the study, ranging between 1.67 dS·m^{-1} and 1.74 mS·cm^{-1}.

Vegetable Compost: The electric conductivity on the first day of the first crop cycle was 3.60 dS·m^{-1}, which decreased over time. At the same time, it is possible to see how the substrate changed from the initial condition to the final, where densification occurred, due to an increase in BD (initial 0.23 kg m^{-3}, end 0.29 kg m^{-3} for both treatments conventional irrigation and management with water restriction). In this sense, this process could be explained due to the management implemented, which was carried out based on previous experience with perlite. In this sense, as result of the irrigation management carried out, this has generated a rearrangement of the particles in time, which generated densification of the substrate, increasing the apparent density.

Mixture: The substrate mixture indicated values ranging between compost and perlite, for the EC`s leachates (2.77 dS·m^{-1}) and the BD (0.17 kg·m^{-3}), indicated in Table 4. During the experiment, the leachate's EC had the same decreasing tendency reported in the compost substrate. Besides, to understand the behavior over time, the final water content (WC) was evaluated together with the measures obtained daily with the tensiometers placed in each substrate.

Effect of temporary water restriction on the substrates

The coir showed a 32% higher water content (% θ conventional irrigation treatment - θ % restricted water treatment); in this sense, the mixture showed poor performance, at 18%. The vegetable compost and perlite had a performance of approximately 25% and 22%, respectively.

Due substrate's different hydric curves (see supplementary information), the point of restriction was not the same for all of them (the minimum hydric potential reached in each substrate was different) because the period of no irrigation was the same in all the substrates (Figure 2). For example, during the first crop cycle, when the perlite presented 19 kPa, the coir and compost presented -23 and 4, respectively. The temporary restriction period was different throughout the three crop cycle s (Table 3) due to the temperature increase during the study, with each crop cycle showing higher temperatures than the previous crop cycle. This induced the same drought stress levels in less time.

Perlite: Focusing on the tensiometers, the perlite water holding capacity (WHC) remained constant through the 3 crop cycle s, with a progressive release of water content over time. When water restriction was induced, the percent drainage variation occurred in hours compared to the other substrates, which took approximately 2 days. Moreover, it was detected that the major differences in the leachate electrical conductivities of the conventional irrigated and restricted perlite bags were related to the duration of the restriction periods and not just to the hydric tension of the substrate. As previously explained, the temperatures increased throughout the second and third crop cycle s, reaching the limiting - 20 kPa in shorter periods. Lower EC values in the second crop cycle (9 days without irrigation) and the third crop cycle (7 days without irrigation) compared to the first crop cycle (14 days without irrigation) once irrigation was restored.

Coir: In crop cycles 1 and 2, the coir showed a slow response to water restriction, but when the matrix potential ranged between 5 and 8 kPa, it decreased rapidly. The results obtained using the water retention curve, a high percent easily available water (23.07%). Its water loss was more progressive than the perlite since perlite has 8.6% easily available water. Moreover, the stress response measure decreased in the last crop cycle with the same hydric demand, and the substrate presented less tension in the pore system. It can explain by the collapse of coarse porosity through the different processes of irrigation and drought in the test, creating a more complex porosity with a normalized pore distribution, which would explain its behavior during test number 3. The treatment with restricted water present a constant EC throughout the study, and no differences were detected in the conventionally irrigated substrates.

Vegetable Compost: Through monitoring with tensiometers, the compost showed a low response to hydric potential in crop cycles 1 and 2 (4 and 17.5 kPa). In the last crop cycle, the compost had similar behavior to perlite in both water restrict treatments (-10/- 20 kPa, with 15 and 25 kPa for compost and 11 and 20 kPa for perlite, Figure 2). The restricted compost's final water content was similar to that of perlite and the water content when the compost was conventionally irrigated. The increase of BD (0.23 to 0.3 kg·m^{-3}) can be explained by the general irrigation management of the test was adjusted to the perlite demands. This could have meant a higher irrigation input during crop cycles 1 and 2, which could have favored particles' arrangement, and for concomitance, the increment of the bulk density. Moreover, when irrigation was stopped, no leachates were detected, and after the water restriction period, the EC was the highest among the substrates.
Specifically, in the first test, the leachates were detected 6 days after irrigation was reestablished, and the electrical conductivity was 4.93 dS·m^{-1}. Nevertheless, this finding highlights that at the end of each crop cycle, the leachates' EC was the same in the restricted crops as in the conventionally irrigated crops.

Mixture: For hydric potential, the mixture showed an intermediate performance between the compost and the perlite in the water restricted treatment during the first crop cycle, while during the second and third crop cycles, it showed a high response to hydric potential, with a lower value (27 kPa) compared to the control (perlite with 20 kPa) (Figure 2). This is consistent with results obtained in the water retention curve easily available water ranged between the values obtained in the compost and the perlite (20.58% and 14.83%, respectively). This could be explained by the mixture having a poor water content performance. The conventionally irrigated and restricted mixture substrates had the lowest WC values (31% and 49%, respectively, compared to the perlite, at 34% and 51%, respectively), confirming the relationship of low water content and low hydric potential (a lower value more strongly strengthens the stress due to the fact that the hydric potential is tension). The BD remained constant over time, being unaffected by the irrigation treatment, and showed an average value of 0.17 kg·m^{-3}; the BDs of the compost and perlite at the start of the crop cycle were 0.23 and 0.11 kg·m^{-3}, respectively. In the end, the compost showed slight compaction (0.29 kg·m^{-3}), but this was not the case in the mixture. The EC was similar, but its behavior was closer to that of the perlite than the compost. The mixture had the same pattern as the compost in the electric conductivity. For example, at the beginning of the crop cycles s, the EC was 2.27 dS·m^{-1} (crop cycle 1), 2.30 dS·m^{-1} (crop cycle 2), and 1.80 dS·m^{-1} (crop cycle 3). Nevertheless, as shown, the differences between the conventionally irrigated treatment and the restricted treatment are smaller than those of the compost.

3.2. Crop production

The crop yields ranged from 245.7 to 490.0 g·plant$^{-1,}$ and some differences were detected due to the substrates, the effect of water restriction, and the meteorological conditions. It is important high light that water supply is key to adequate food production, however there are studies have shown that the water content of a media has a direct influence on the fresh weight gain by lettuce plants[23]. The compost and the mixture presented the same or better results than the control treatment, this can be explained by several reasons. The first is due to the high cation exchange capacity (CEC) of compost, which has a series of nutritional advantages, in contrast to perlite, which has a low CEC [24] value. In this sense, the compost can present a buffer effect, retaining a greater amount of nutrients, which can be made available to the plant[25]. This higher content of nutrients could be associated with the electrical conductivity in the compost, it was always higher than in the rest of the treatments (Table 4). At the same time, the presence of compost (100% or 50%) is associated with an increase in biological activity in the substrate. Although this is a parameter that we have not measured, there is research on the positive effect of the presence of organic matter, in this case, compost. Several positive interactions given by the presence of biological activity can be mentioned, like the suppressive effects against pathogens[26,27], the improvement of nutrient availability, which could be related to the higher performance obtained by this substrates.

With our results it is possible to appreciate that when the hydric restrictions are generated losses of yield, in general, the smaller this loss, the greater tolerance to the hydric deficit the substrate presents. The main result is that in all three alternative substrates studied, commercial productions were obtained; therefore, they could be used in UA. As expected, when the crops suffered under a water restriction period, production decreased, but the magnitude of these losses was different among the substrates.

Conventional irrigation

During the first crop cycle (April), when the crops were irrigated appropriately, no significant differences ($p<0.05$) in the yield were observed among the substrates. The yield obtained ranged between 422.7 and 445.7 g·plant^{-1}. Crop cycle 2 present a different behavior, with the conventional irrigation, crops grown on the mixture and coir substrates obtained statistically the same production as the control (which is the substrate with the highest production: 490.0 g·plant^{-1}), and the compost presented the lowest production (423.9 g·plant^{-1}, 14% less weight). In 3 crop cycle, the best results in the conventional irrigated crops were obtained with compost (408.7 g·plant^{-1}) and mixture (418.4 g·plant$^{-}{}_{1}$). Compared to the substrate with the highest obtained weight (mixture) presented the lowest production (370.1 g·plant^{-1}), -11.5% less. The behavior of the compost was notably different from those of the other substrates. The lettuce grown in the compost presented successive decreasing weights with the three consecutive crop cycles (Table 5). This difference could be due to the fact that in the first crop cycle, the compost is used for the first time, being able to contribute a large amount of nutrients to the lettuce. However, throughout the trials, nutrient depletion was detected by measuring the electrical conductivity of the leachates, as noted in the previous section.

Water stress effect on the yield

Some differences were detected when the crops were under water restriction. Compared to the control, the mixture, and the coir substrates in the first crop cycle, the plants grown in the compost reached higher weights (322.6 g·plant^{-1}). As mentioned previously, the increase extreme heatwaves are one of the effects that are expected due to climate change, in the same way, the reduction of water availability in per crop seasons, our results show the viability of the use of organic substrates from urban green waste is a competitive agronomic option for use in UA. Thus, the compost was able to provide some buffering capacity to the temporary drought. Previous research has shown the feasibility of organic substrates such as compost and its derivatives [26], and how environmentally it presents a better performance in terms of nutrient supply and carbon sequestration [28], relevant point to reduce the effects on climate change. In this regard, it is vital to focus on develop research for substrates that have a low environmental impact, and that are economically viable, with high local availability [11].

The coir did not reduce stress in the lettuce as much as expected based on the material's high water-retention capacity. Previous studies have suggested that the yield decrease could have been due to excessive osmotic stress from the combined effects of the drought and the high salinity of the media, which would not have been reflected in the tensiometer readings, as these only report matric potential (not osmotic) [29].

In the second crop cycle, in all the treatments, compared to the conventional irrigated crops, the water restricted crops' production decreased and was statistically the same between treatments. In this case, the compost results were worse than expected. First, the lettuce presented the same weight as the other substrates, and the benefits detected in the previous crop cycle were not detected here. Second, because the other three restricted substrates presented an increase in production compared to the first crop cycle (25-30%), compost's production was similar to that in the first crop cycle (320 g).

Compared to the previous crop cycles, during the third crop cycle, the higher temperatures induced a more rapid appearance of water stress (Figure 2). Whether the water restriction reached -10 kPa or -20 kPa, the lowest production was obtained in the perlite bags. When the restriction reached -20 kPa, the mixture and the compost substrates presented the best results (295.2 and 284.9 g·plant^{-1}, respectively). Nevertheless, when the restriction did not exceed -10 kPa, the crops grown in the coir, and the mixture reached the highest production values (358.9 and 350.3 g·plant^{-1}). These results could have been perceived when analyzing the water loss curves of the different substrates. As shown in the previous section, in the first crop cycle, the coir took a long time to lose water; however, when dryness begins, water loss occurs very quickly and can damage crop production.

3.3. Relevance in UA

The consumption model within cities is characterized by being unidirectional, where inputs and outputs flow prevail. [30] Firstly, diverse externalities are generated by an extractives model that feeds on natural resources, and secondly, it increases new spaces for agricultural production to satisfy the city's requirements. From a circular economy perspective, favor exchanges of flows between urban subsystems are part of the solution to migrate to sustainable cities [31]. The use of compost and the mixtures of substrates derived from it, responds to these needs since at the city level 1; it reduces and values municipal solid waste (MSW), 2; favors the recycling of nutrients, 3; as a substrate to improve physical, chemical and biological properties of the culture medium.

(1) By using organic matter from MSW its amount will be reduced and, therefore, the greenhouse gases emitted in landfill disposal [32]. In this sense, the advantages can be seen at the UA level and interact with more elements within the city [33]. Other Research presents a study in Belgium about the opportunities and barriers of compost at the farm level, where they recommended 5 measures towards using compost[34]. However, the study is carried out for farm conditions, the recommendations are applicable in a circular economy context in the city. The third recommendation refers to searching for new alternative sources of biomass from other industries to produce compost. It is possible to find different stakeholders at the city level that can regularly provide biomass, such as greengrocers and coffee shops, among others. The integration of agricultural production in the city would maintain a stable compost production over time due to its possible interconnections to other industries. Furthermore, research has been made on composting with common inorganic waste from the city, which has shown good results, such as disposable diapers and biochar, among others. [35–37].

(2) By composting the organic matter, it stabilizes, and the nutrients are available again to produce new vegetables [38,39]. Since nutrients are a limited resource, reincorporating and reusing them in the production system is vital for the UA's sustainable development.

(3) The incorporation of compost (total or partially) as a replacement for commercial substrates can decrease the CO_2 emissions, depending on the origin of the replaced substrate. As an example, for this, in Spain, close to 80% of the perlite used comes from Turkey, South Africa, Greece, Uganda, and United Kingdom (35%, 18%, 10%, 8%and 8% respectively), where the reduction in the transport item could result in an environmentally better process. Studies suggest that under proper compost management, environmental impacts are reduced [40].

In the present study, the vegetable compost and the mixture of vegetable compost with perlite are suitable substrates in horticulture, especially in RA. Besides, it has been observed that these substrates have better characteristics for preventing hydric stress in summer, despite previous studies showing that compost production could decrease due to salt concentrations [41].

The yield was markedly competitive and higher than that of perlite in April and July. Lettuce is a moderately sensitive crop to salinity, similar to most of the RA crops: pepper, tomato, and spinach, among others. Therefore, the results obtained in this study could be directly applied to other horticultural crops.

4. Conclusions

This analysis quantified lettuce’sagronomic performance grown in organic substrates, including their resilience to temporary water restriction. In the circular city context, the study of the agricultural performance of environmentally friendly substrates (the recycled organic municipal waste in cities) can contribute to RA implementation in Mediterranean urban areas. Our results show that the studied organic substrates, coir, as a commercial substrate, and vegetable compost alone or in a substrate mixture with perlite 1:1, could be used in UA, as they obtained similar or higher production than the control substrate (perlite). In summer, the best results were obtained with vegetable compost alone (408.7 g·plant^{-1}) and compost mixed with perlite (1:1) (418.4 g·plant^{-1}). Nevertheless, a sequential decrease in the fresh lettuce weight grown in compost in the three crop cycles was detected, probably due to the substrate’s loss of nutrients.

We found that compared to perlite, the organic substrates improved the conditions against applied water restriction and increased the crops’ yield. Specifically, the coir tended to take a long time to lose water; however, when dryness begins, it occurs very quickly, and commercial production decreases if drought induces water stress of -20 kPa, the compost and the mixture of compost and perlite present remarkable agronomic resilience.

5. Acknowledgments

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6. Conflict of Interest Statement

The authors do not present any type of conflict of interest.

7. Author contribution

All authors were responsible for the conception and design of the study conceived, M. Ercilla-Montserrat, N. Carazo, J. I. Montero, X. Gabarrell, G. Villalba, J. Rieradevall, E. Lopez-Capel, P. Muñoz, the original idea for the study. M. Ercilla-Montserrat, F. Parada, V. Arcas-Pilz, and P. Muñoz set up, supervised and acquired the data for the experimental tests. N. Carazo for laboratory analysis. F. Parada and M. Ercilla-Montserrat processed and analyzed the data and took the lead in writing the manuscript. All authors critically revised the draft for important intellectual content. All authors gave their final approval to the manuscript.

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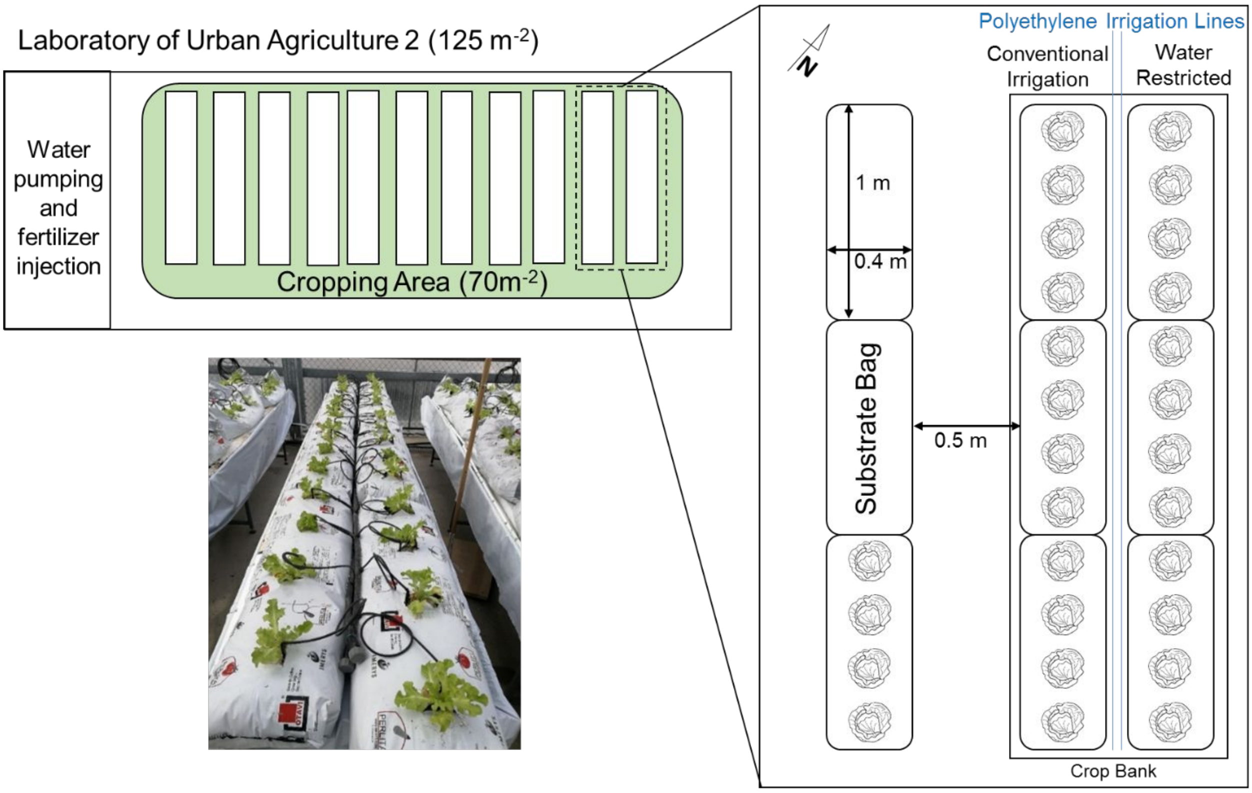

Figure 1 Image and diagram of experimental design of lettuce cultivation system.

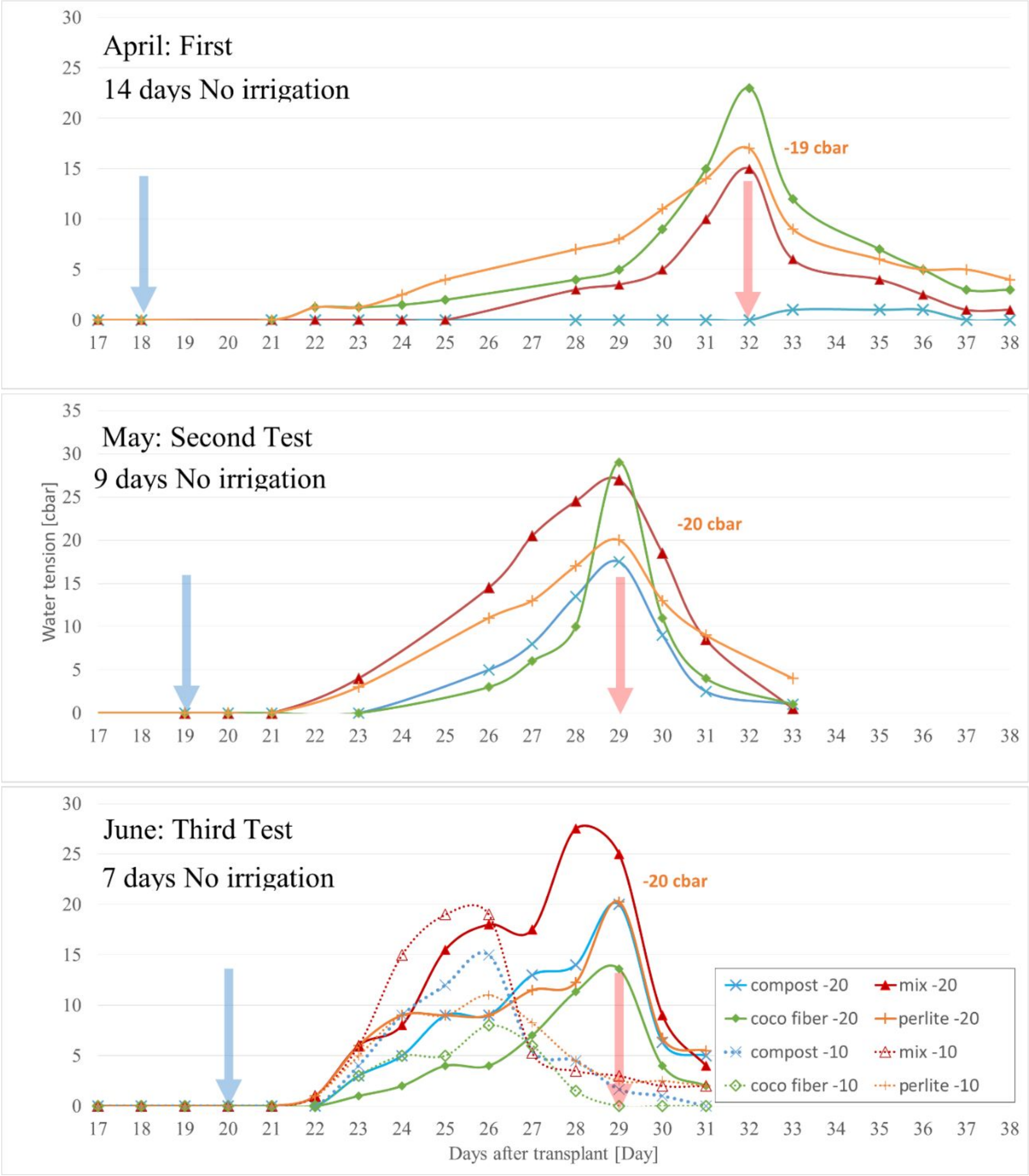

Figure 2. Water tension inside each substrate's bags under study after inducing water restriction up to -20 cbar (tests 1, 2 and 3) and -10 cbar (test 3). Tested substrates: vegetable compost, a mixture (mix in the Figure) of compost and perlite in a 1:1 volume, coir and perlite (the control substrate). The blue arrow shows the beginning of cut of irrigation. The red arrow shows the reincorporation of irrigation.

Table 1. Substrate physical and chemical properties.

Subtrate	Total Porosity	Granulometry	pH	Electric Conductivity	Organic Matter	Origin
	%	mm		$dS \cdot m^{-1}$	%	
perlite	95.8	0 to 6*	7*	0.09*	1.1	Inorganic. Expanded clay, chemically inert
coir	92.2	-	6	0.45	85	Coir and coco dust
compost	87.2	0 to 10	8	2.77	60	Municipal pruning waste, Composting process takes up to 3 months to finish on open-air piles
mixture	91.4	0 to 10	7	1.43	30	-

*perlite`s physical and chemical properties were provided by the commercial company provider (OTAVI, S&B ®). The total porosity of growing media was estimated based on the content of organic and mineralogical matter of each of the substrates. (For more details see the Supplementary Information).

Table 2. Average temperature and relative humidity conditions inside and outside of integrated rooftop greenhouse (i-RTG).

	Crop cycle	Temperature C°			Relative humidity %		
		Avg.	**Max.**	**Min.**	**Avg.**	**Max.**	**Min.**
Inside	1	19.6	31.7	11.3	43.9	68.0	9.2
	2	20.5	29.9	14.4	60.5	86.2	25.2
	3	26.0	35.8	18.6	53.6	83.2	19.2
Outside	1	13.2	23.0	1.5	69.5	100.0	17.3
	2	18.3	25.5	8.4	71.4	100.0	30.4
	3	24.49	30.8	17.9	62.72	100.0	30.3

Table 3. Crop cycle schedule greenhouse.

		Crop cycle						
Date		**1st**		**2nd**		**3rd**		
Transplanting		19/3/2018		3/5/2018		19/6/2018		
Harvest		26/4/2018		4/6/2018		18/7/2018		
Growing season		43 days		33 days		29 days		
Treatments		No stress	Restriction	No stress	Restriction	No stress	Restriction	Restriction
		0 to-5 cbar	-20 cbar	0 to-5 cbar	-20 cbar	0 to-5 cbar	-10 cbar	-20 cbar
Hydric restriction	**Start**		6/4/2018		22/5/2018		9/7/2018	9/7/2018
	End		20/4/2018		31/5/2018		13/7/2018	16/7/2018

Table 4. Physical characterization of substrates.

Substrates	Irrigation	Bulk density (Mean±SD)		WC (Mean±SD)		Differential at the end of the study	Electrical Conductivity Leachates	
		Start	End	Start	End		Start	End
		kg·m^{-3}		θ % (Vol water / Vol soil)		θ%C- θ%R	dS·m^{-1}	
vegetable compost	**R**	0.23 ±0.02^{a} (n=4)	0.29±0.04 (n=6)	31.62 ±0.99^{b} (n=4)	38.12±17.92^{d} (n=6)	25.48	4.03	2.27
	C		0.29±0.03 (n=6)		63.60±4.27^{ab} (n=6)		3.60	1.94
coir	**R**	0.09 ±0.00^{d} (n=4)	0.09±0.02 (n=6)	81.76 ±1.71^{a} (n=4)	38.35±6.79^{d} (n=6)	32.8	1.59	1.84
	C		0.10±0.01 (n=6)		71.15±5.41^{a} (n=6)		1.67	1.74
mixture	**R**	0.17 ±0.00^{b} (n=4)	0.18±0.03 (n=6)	25.29 ±8.46^{bc} (n=4)	31.26±4.58^{d} (n=6)	17.87	2.27	1.90
	C		0.17±0.03 (n=6)		49.13±4.23^{c} (n=6)		2.77	1.59
perlite	**R**	0.11 ±0.01^{c} (n=4)	0.12±0.01 (n=4)	14.43 ±15.96^{c} (n=4)	34.92±1.96^{d} (n=4)	21.96	0.83	1.92
	C		0.12±0.03 (n=4)		56.89±4.88^{bc} (n=4)		0.86	1.50

R: Restricted (-20cbar), C: Conventional, WC: water content, and EC: electrical conductivity in the leachates. SD standard deviation.

Table 5. Fresh yield (fresh mass g/plant) of lettuce grown in green compost, coir, perlite and compost/perlite mixture (1:1) under conventional irrigation and restricted temporary drought; where the same substrates are used for 3 crop cycles.

Month	Treatment	compost		mixture		coir		perlite	
		g·plant^{-1}							
1st crop cycle April 2018	Conventional - irrigation	445.7	a	427.1	a	422.7	a	445.0	a
	Restricted -20	322.6	b	*249.2*	*c*	*277.5*	*c*	*259.3*	*c*
2nd crop cycle May 2018	Conventional - irrigation	423.9	b	477.2	ab	453.7	ab	490.0	a
	Restricted -20	*320.2*	*c*	*323.5*	*c*	*348.5*	*c*	*340.7*	*c*
3rd crop cycle July 2018	Conventional - irrigation	408. 7	ab	418.4	a	370.3	c	381.8	bc
	Restricted -10	336.3	ed	350.3	cde	358.9	cd	322.4	f
	Restricted -20	285.0	g	295.2	g	*276.1*	*gh*	*245.7*	*h*

Values are mean (n = 15 for organic substrates or mixture; n = 10 for perlite) for conventional and restricted temporary drought. Means followed by a different letter indicate significant differences in the same row (This corresponds to the comparisons between the treatments within each month/crop cycle).