Comparison of organic substrates in urban rooftop agriculture, towards improving crop production resilience to water stress 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 meet food production demand in cities. In a context of low water availability, it is important to consider alternatives that are able to maintain production. This study aimed to assess the use of substrates made from local materials and high water retention capacity as an alternative for urban agriculture in periods with water stress. Different substrates were used for 3 consecutive crop cycles of lettuce (*Lactuca sativa* L.) during the spring and summer periods of 2018 to observe these substrates performance during warmer periods of the year in an integrated rooftop greenhouse near Barcelona. The substrates used were coir commercial organic substrate, vegetable Compost from urban organic waste, Perlite (as control) commercial standard substrate, and a Mixture of the urban Compost and Perlite (1:1). Substrate crop performance was assessed under conventionally irrigation (0-5 cbar) and water restricted conditions (irrigation stop until the water tension inside the perlite bags reached -20 cbar). RESULTS: The results demonstrate that the Compost and Mix yields were similar to those obtained from Perlite (11.5% y 3.7% of more production in a restricted water condition average values). Compared to the Perlite, the organic substrates increased the crops resilience to water restriction, through biomass accumulation comparison, it took longer for Coir to lose water (1 and 2 test); however, when dryness began, it occurred very quickly. CONCLUSION: The vegetable Compost and the substrate Mixture presented tolerance to water restriction when water restriction reached -20 cbar.

Keywords: Circular economy, sustainable cities, soilless system, water stress resilience, 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, causing persistent droughts, one of the biggest problems to be addressed in agriculture due to the high water demand for food production [1].

Urban agriculture (UA) is an alternative that originated to satisfy the higher demand, contributing to food production's sustainability by reducing different production chain elements, such as energy in distribution and used packaging [2]. UA can be carried out at different levels: Rooftop Agriculture (RA) (3) on the ground and on building rooftops. 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 [4]. The evaluation of unoccupied roof spaces for rooftop greenhouse (RTGs) 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 [5].

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. This highlights the importance to develop alternatives to alleviate drought conditions of urban crop systems and maintain the 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 (SCSs). SCSs, is frequently used to establish crops in an artificial medium to produce food under different growing conditions [6]. A variety of organic and inorganic substrates could be suitable for crop production under restricted water availability.

One of the most used substrates is Perlite, an inorganic grow media 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 [7]. 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 minimal geographical areas far from maximum horticultural use and present the same Perlite problem on transportation. Compost is an alternative to Coir [8], since it is possible to obtain it locally, avoiding transportation. Compost is produced from local organic waste, which is highly available at city levels. This is nutrient rich, therefore reducing the need of use of nutrient solution. 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 growing need to easy to manage, have a low environmental impact, show high moisture retention, and have nutrients that are readily available for crops.

Organic substrates have been widely studied for their use in the horticultural industry [9–11] but not in the UA circular economy context. There is an urge in both horticultural industry and gardening (including UA) 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 [12], and their reuse as substrates might provide a suitable solution [13]. 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)

[14] 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 the use of Compost as an alternative growing media to Perlite and Coir, in terms of comparable crop production and lower environmental impacts. A better understanding of the use of urban and agricultural residues as substrates for urban crop production will contribute towards meeting SGDs 2 and 11 and urban circular economy approach. 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 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 [15]. 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 weather conditions in the i-RTG Lab were passively controlled.

2.2. Substrate characteristics

The present study focused on three growing media substrates. These consist of: Perlite as control substrate, Coir, Compost from municipal vegetal wastes, and a (1:1) Mixture of the vegetal Compost and Perlite. Growing media physical and chemical properties as shown in Table 1.

2.3. Experimental design

The experiment consisted of monitoring substrates performance during 3 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 in Table 2.

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

A 70 m2 study area within the 125 m2 i-RTG facility was used. Growing bags' dimensions were 0.4 m x1.0 m, and they had a volume of 40 L. Each plant was planted at distances of 0.2 m x 0.4 m resulting in 4 plants per growing media bag, three bags per rows, and 0.5 meter distance between rows, as shown in Figure 1. Oak leaf lettuces (*Lactuca sativa* L. var. Intybacea) seedlings were planted in the 4 substrates. Crop growth was monitored and growing conditions controlled, following conventional agronomic guidelines for lettuce production). During the growing periods, diseases and deficiencies detected in the crops were also monitored.

2.4. Irrigation management

The Nutrition solution was provided to the lettuces via a drip fertigation system. The nutrient solution contained: HNO_3 63 mg·L^{-1}, KPO_4H_2 136 mg·L^{-1}, KNO_3 101 mg·L^{-1}, K_2SO_4 174 mg·L^{-1}, $Ca(NO_3)_2$ 164 mg·L^{-1}, $CaCl_2$ 111 mg·L^{-1}, $Mg(NO_3)_2$ 148.3 mg·L^{-1}, and microelements 0.1 mg·L^{-1}.) Irrigation volumes were adapted and optimized to the needs of lettuces grown in the control media (perlite substrate). They ranged between 0.3-0.45 L·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. [16]. This restriction was applied by completely stopping irrigation until the perlite bags reached -20 cbar. At this time, irrigation was reestablished for all the water restricted rows. Water tension in the growing media was determined with an analog 12 cm tensiometer (irrometer® MLT) through the hydric potential variation, with a range of 0 to -40 cbar. Also, in the third crop cycle, a second 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 cbar.

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 tests, and the amount of irrigated water, the leachates drained, and its conductivity was measured (Table 4). The characterization of the substrate was made by the bulk density test (at the start and end of the completely essay), this was performed for each growth medium by the ring method (USDA, 1999); indicating the amount of water, the porosity and the bulk density. 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

Five crop samples were taken randomly from different repetitions of each treatment. At the end of the test, when the crop was harvested, the final yield was determined (g of the commercial part of lettuce, Table 5). For the commercial weight, 5 plants in each crop line were selected randomly, while for the water content determination, 3 plants were also selected randomly in each line.

2.7. Statistical analysis

The crop measurements were expressed using average values and standard deviations. “R” version 3.1.2 software [17] was used to determine significant differences between the different substrates and the effect of 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 and Levene. Multiple comparisons of the means were determined by a post hoc Duncan test. When the data were not normally distributed, 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 test. Within the third test it was possible to appreciate a lower variability between the yields of plants irrigated conventionally and with water restriction. In addition, a trend towards a reduction in yield, regarding on the applied water restriction (-10 and -20 cbar).

3.1. 3.1. Substrate characteristics

At the end of the three consecutive experiments, the bulk density (BD) for each growing medium was determined and is shown in Table 4. This information allows us to describe each substrate's porosity system behavior under conventional irrigation and water restriction. The 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 g·cm^{-3}, followed by Perlite, Mix, and Compost, the latter with 0.23 g·cm^{-3} (Table 4).

Perlite: In this study, it was not possible to see final compaction of this growing media, which was possible in all the other substrates. The leachates' conductivity in the conventional irrigation ranged between 0.86 mS·cm^{-1} and 1.90 mS·cm^{-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 (57.00%), there was a 14% higher WC in the Coir. Additionally, the Coir showed the smallest BD of all the growing media used in this assay, with 0.1 g·cm^{-3}. In other word present a very low weight and high water retention, characteristic desirable in a substrate. The Coir's conductivity was constant throughout the study, ranging between 1.59 mS·cm^{-1} and 1.70 mS·cm^{-1}.

Vegetable Compost: The conductivity on the first day of the first test was 3.80 mS·cm^{-1}, which decreased over time, down to 3.40 mS·cm^{-1} and 2.10 mS·cm^{-1} at the beginning of the two other tests. At the end of the study, the Compost leachates had a conductivity of 1.90 mS·cm^{-1}.

Mixture: The substrate Mixture indicated values ranging between Compost and Perlite, for the EC`s leachates (2.27 mS·cm^{-1}) and the BD (0.17 g·cm^{-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 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 to each growing media's different hydric curves, 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 test, when the Perlite presented 19 cbar, the Coir and Compost presented -23 and 4, respectively. The restriction period was different throughout the three tests (Table 3) due to the temperature increase during the study, with each test showing higher temperatures than the previous test. This induced the same water stress levels in less time.

Perlite: Focusing on the tensiometers, the perlite water holding capacity (WHC) remained constant through the 3 tests, 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. After the restriction period, the EC was very high at 3.45 $mS·cm^{-1}$, 2.95 $mS·cm^{-1}$, and 2.52 $mS·cm^{-1}$ for each consecutive test, indicating a higher concentration of salts in the bag. 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 tests, reaching the limiting - 20 cbar in shorter periods. Lower EC values in the second test (9 days without irrigation) and the third test (7 days without irrigation) compared to the first test (14 days without irrigation) once irrigation was restored.

Coir: In tests 1 and 2, the Coir showed a slow response to water restriction, but when the matrix potential ranged between 5 and 8 cbar, it decreased rapidly. The results obtained using the water retention curve, a high percent available water (27.60%), especially easily available water (23.06%). Its water loss was more progressive than the Perlite since Perlite has 19.49% available water and 8.25% easily available water. Moreover, the stress response measure decreased in the last test with the same hydric demand, and the growing media 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 essay, 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 tests 1 and 2 (4 and 17.5 cbar). In the last test, the Compost had similar behavior to Perlite in both water restrict treatments (-10/- 20 cbar, with 15 and 25 cbar for Compost and 11 and 20 cbar for Perlite, Figure 2). Compost presented a similar available water content (20.67%) as Perlite, but the percent easily available water was higher (17.23%). 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 $g·cm^{-3}$) can be explained by the general irrigation management of the essay was adjusted to the perlite demands. This could have meant a higher irrigation input during tests 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 conductivity was 4.70 $mS·cm^{-1}$. For the other two tests, the leachates were recovered after two days, and the conductivity was 3.70 $mS·cm^{-1}$ and 2.20

mS·cm^{-1}. Nevertheless, this finding highlights that at the end of each test, 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 test, while during the second and third tests, it showed a high response to hydric potential, with a lower value (27 cbar) compared to the control (Perlite with 20 cbar) (Figure 2). This is consistent with results obtained in the water retention curve as the percent available water and the easily available water ranged between the values obtained in the Compost and the Perlite (19.20% and 11.79%, respectively). This could be explained by the Mix 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 g·cm^{-3}; the BDs of the Compost and Perlite at the start of the essay were 0.23 and 0.11 g·cm^{-3}, respectively. In the end, the Compost showed slight compaction (0.29 g·cm^{-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, but the conductivity was approximately the average between the EC in the Compost and the Perlite. For example, at the beginning of the three tests, the EC was 2.50 mS·cm^{-1} (test 1), 3.30 mS·cm^{-1} (test 2), and 1.80 mS·cm^{-1} (test 3). The highest values after the restricted period were 2.87 mS·cm^{-1} (test 1), 2.36 mS·cm^{-1} (test 2) and 2.20 mS·cm^{-1} (test 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. Studies have shown that the water content of a media has a direct influence on the fresh weight gain by lettuce plants [18]. 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 test (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}. Comparing tests 1 and 2, different results were obtained. In test 2, when appropriated irrigation was applied, the 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 test, 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), the Coir 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 tests (Table 5). This difference could be due to the fact that in the first test, the vegetable Compost was new and could provide a large quantity of nutrients to the lettuce. However, in May, a nutrient depletion was detected by measuring the leachates' electric conductivity, as noted in the previous section. The Compost leachates' EC ranged between 4.77 and 3.60 $mS\cdot cm^{-1}$ in April, between 3.70 and 2.47 $mS\cdot cm^{-1}$ in May, and between 2.8 $mS\cdot cm^{-1}$ and 2.2 $mS\cdot cm^{-1}$ in July. Furthermore, a compaction of the substrate was detected, which could be a further reason for the production decrease [19].

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 test, the plants grown in the Compost reached higher weights (322.6 $g\cdot plant^{-1}$). These results agree with Mastouri et al.[19], who detected that the growth of lettuce increased as the contribution of either type of Compost in the growing media increased, where the production in the soil obtained in that study was 282.2 $g\cdot plant^{-1}$, and the highest production using a Mixture of tree bark Compost was 308.9 $g\cdot plant^{-1}$. These results demonstrate that vegetable Compost 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. 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) [20]. As previously shown, the leachates' EC did not change after the water restriction periods, which could cause a concentration of salts in the substrate.

In the second test, 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 test were not detected here. Second, because the other three restricted substrates presented an increase in production compared to the first test (25-30%), Compost's production was similar to that in the first test (320 g).

Compared to the previous tests, during the third test, the higher temperatures induced a more rapid appearance of water stress (Figure 2). Whether the water restriction reached -10 cbar or -20 cbar, the lowest production was obtained in the perlite bags. When the restriction reached -20 cbar, the Mixture and the Compost substrates presented the best results (295.2 and 284.9 $g\cdot plant^{-1}$, respectively). Nevertheless, when the restriction did not exceed -10 cbar, the crops grown in the Coir, and the Mixture reached the highest production values (358.9 and 350.3 $g\cdot plant^{-1}$). 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 test, 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. [21] 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 [22]. 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 [23]. In this sense, the advantages can be seen at the UA level and interact with more elements within the city [24]. Viaene et al., (2016) [25] present a study in Belgium about the opportunities and barriers of Compost at the farm level, where they recommended 5 measures towards using Compost. 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. [26–28].
(2) By Composting the organic matter, it stabilizes, and the nutrients are available again to produce new vegetables [29,30]. 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 [31].

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 [19].

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's agronomic performance grown in organic substrates, including their resilience to 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. Previous studies have addressed the environmental impacts and benefits of using Coir and Compost as substrates [6,32] while considering the development of crop and commercial production. 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 $g \cdot plant^{-1}$) and Compost mixed with Perlite (1:1) (418.4 $g \cdot plant^{-1}$). Nevertheless, a sequential decrease in the fresh lettuce weight grown in Compost in the three tests was detected, probably due to the substrate's loss of nutrients.

We also presented the first quantitative assessment of the agronomic response of water restriction conditions in three alternative substrates of Perlite in the urban Mediterranean context. 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 cbar, the Compost and the Mixture of Compost and Perlite present remarkable agronomic resilience.

These results contribute to UA's knowledge and preventive measures of droughts in Mediterranean cities with quantified data. In the current climate change context, with increasing droughts in summer, commercial systems that utilize Compost as a growing media could reduce irrigation frequency, save water without increasing the substrate's salinity, and still produce commercially relevant yields. However, further studies should determine the optimal irrigation and nutrient inputs for improving the growing conditions to increase harvest weight. Additionally, this optimization could minimize the environmental impacts for a lettuce unit, and kg of lettuce should be studied in a detailed life-cycle assessment. More research is needed to contribute to this substrate's environmental analysis, considering the substrates' lifespan and their waste management impacts.

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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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