Simplified hydroponics in Tunisia: assessing the charred straw as growing substrate for lettuce cultivation

This is the submitted version (pre peer-review, preprint) of the following publication:

Published Version:
Cerasola, V.A., Jmayai, A., Viola, F., Jamai, D., Adamo, F., Costea, C., et al. (2025). Simplified hydroponics in Tunisia: assessing the charred straw as growing substrate for lettuce cultivation. Leuven : International Society for Horticultural Science (ISHS) [10.17660/actahortic.2025.1422.4].

Availability:
This version is available at: https://hdl.handle.net/11585/1011226 since: 2025-03-28

Published:
DOI: http://doi.org/10.17660/actahortic.2025.1422.4

Simplified hydroponics in Tunisia: assessing the charred straw as growing substrate for lettuce cultivation

V.A. Cerasola[1], A. Jmayai[2], F. Viola[2], D. Jamai[2], F. Adamo[2], C. Costea[2], G. Pennisi[1], F. Orsini[1], N. Michelon[1], M. Setti[1], G. Gianquinto[1]

[1]Department of Agricultural and Food Science, Alma Mater Studiorum University of Bologna; [2]CEFA Onlus

Abstract

Simplified hydroponics proves to be a viable solution for sustainable vegetable production in developing economies. In a rural area of Northern Tunisia lacking commercial growing media, a three-replicated randomized block design experiment assessed the agronomic efficiency of an alternative growing substrate for lettuce cultivation. A closed-loop hydroponic system with gravity irrigation utilized recovered plastic bottles as pots, arranged in 2 m long rows and tilted to ensure nutrient solution flow. Tested substrates were commercial perlite and locally recovered wheat straw that was charred. Plants were sampled at the top, middle, and bottom of the row. Charred straw at the top of the system yielded the highest, although productivity declined in the row middle and bottom. When the adopted substrate was perlite yield was consistent across the different positions in the raw, with values comparable with those from plants on charred straw in the middle and bottom positions. These results suggest limited drainage in charred straw, impacting nutrient solution flow through the bottom of the system. Additionally, plant dry matter (%) was significantly higher in perlite, and increased at the bottom of the system for both substrates. Strategic interventions are needed to address limitations in drainage properties, thereby optimizing the potential of charred straw as a viable hydroponic substrate. Preliminary findings on using optical sensors for lettuce yield estimation in simplified hydroponics are presented, while system productivity improvements are discussed. The study provides valuable data supporting the implementation and optimization of simplified hydroponics production in Northern Tunisia.

Keywords: simplified soilless system, growing media, circularity, leafy vegetables, optical sensors, yield estimation

INTRODUCTION

Agriculture assumes a pivotal role in addressing global food challenges, especially countries with developing economies. Moreover, the entire Mediterranean basin, including Tunisia, faces the impacts of ongoing climate change, which are anticipated to exacerbate the water scarcity in the region (Dakhlaoui et al., 2020). Despite the fact that northern Tunisia contributes significantly to the country's surface water (Dakhlaoui et al., 2020), local farmers have reported an increasing incidence of drought in recent years, adversely affecting crop yields and income (Pechan et al., 2023). In response to these challenges, simplified hydroponics emerges as an innovative agricultural solution, promoting efficient and sustainable food production. Simultaneously, it diminishes reliance on traditional resources like soil and water, aligning with the principles of the circular economy (Michelon et al., 2020). Hydroponics facilitates plant cultivation in liquid nutrient solutions, eliminating the need for traditional agricultural soil. It enables more efficient water use through closed-loop systems and provides opportunities for growing food in urban environments or on less fertile soils (Orsini et al., 2013). Moreover, the utilization of recycled materials, such as wood, plastic, or agricultural by-products, makes simplified hydroponics economically accessible and environmentally sustainable (Orsini et al., 2009). The versatility of simplified hydroponics allows for the cultivation of a diverse range of crops, thereby enhancing food diversification and security in these regions. However, the choice of growing substrates is critical in hydroponic systems, influencing water and nutrient retention as well as crop yield (Michelon et al., 2021). Notwithstanding, commercial substrates like perlite and rockwool may not be readily available in remote rural areas. Exploring alternative growing substrates derived from recovered agricultural byproducts presents a viable option, although their agronomic effectiveness necessitates experimental evaluation. The present paper aims to explore the agronomic performance of carbonized wheat straw as a potential alternative to commercial perlite for lettuce cultivation in a simplified hydroponic system in the rural area of Fernana (Jendouba governorate, Northern Tunisia). Furthermore, preliminary results on potential use of optical sensors (SPAD) for monitoring crop yield are presented.

MATERIALS AND METHODS

The hydroponic system used and experimental design

In a 2022 experiment, romaine lettuce (*Lactuca sativa*) was cultivated in a hydroponic system to assess the agronomic performance of charred wheat straw in comparison to commercial perlite. On-site production of charred straw utilized a hand-made furnace, repurposing perforated tin, and a wheelbarrow as a container for carbonization. The randomized block design experiment, with three replicates, occurred during the fall growing season from November 1 to December 15 (45 days). The lettuce plants were manually transplanted at a density of 29 plants m^{-2} in a closed-loop simplified hydroponic system located in a local school in the rural area of Fernena (36.61 N°, 8.81 E°). The hydroponic system employed plastic bottles repurposed as pots, joined in lines and tilted on a 24% slope to facilitate gravity flow of the nutrient solution. Each line consisted of 6 bottles, accommodating 12 plants. The nutrient solution, stored in an upper tank at a height of 2.5 m, was delivered to the first bottle of each line through a gravity drip irrigation system. The solution flowed along the tilted bottles to the bottom, where a drainage system collected excess nutrient solution, stored in lower tanks for subsequent recirculation in the system. For more details on the hydroponic system, refer to Michelon et al. (2020). The nutrient solution, with an electrical conductivity (EC) of 1800 uS cm^{-1}, was prepared by blending mineral fertilizer in water. The mineral fertilizer included commercial NPK+microelements, Calcium CaO, and Mg-Sulphate. pH was maintained at the optimal level of 6 using phosphoric acid.

Data collection and statistical analysis

At harvest, ten plants per replicate were sampled, excluding the first and last plants of the row to mitigate border effects. The SPAD meter (Konica Minolta, Warrington, UK) assessed the nutritional status. Subsequently, total and marketable fresh weight (TFW and MFW) were determined. After oven drying at 72 °C until constant weight, dry weight (DW) was recorded, and Plant Dry Matter (PDM, %) was calculated. The hydroponic system was divided into three sections based on plant position (top: 1st to 3rd plants, middle: 4th to 7th, bottom: 8th to 10th), and samples were maintained separated to assess positional effects. Daily maximum and minimum air temperatures were monitored near the hydroponic system with electronic thermometer. Crop evapotranspiration (ETc) was calculated using the Hargreaves-Samani formula (Hargreaves and Samani, 1985), as it was evaluated as an accurate method to estimate ETc in Tunisia (Jabloun and Sahli, 2008), and Kc was derived from Allen et al.

(1998). Total water consumption was recorded, and Water Use Efficiency (WUE, g FW m^{-2} L^{-1}) was calculated following Michelon et al. (2020).

Statistical analyses were performed using R Studio software (version 4.2.0, packages emmeans and car) using one-way and two-way ANOVA. Tukey test separated means, and assumptions of normality and homoscedasticity were verified by Shapiro-Wilk and Levene tests, respectively. Non-parametric Kruskal-Wallis test was used if assumptions were not met, and Dunn test was used to separate the medians. Non-linear regression assessed whether SPAD values can be used to predict lettuce yield. Relative yield was used to normalize the substrate effects, and was calculated by dividing the observed plant weight by the highest weight in a given substrate (Gianquinto et al., 2004).

RESULTS AND DISCUSSION

Agronomic performances of the charred straw

Significant interactions between the substrate and the position of the plant in the system were observed for TFW, MFW, DW, and SPAD, while PDM was affected both by the position and substrate (Table 1).

Table 1 Two-way ANOVA analysis between Substrate (S) and Plant position (P) in the system for different agronomical parameters. Asterisks indicate significant difference (at $p<0.05$, 0.005, and 0.001 respectively for *, **, ***), while ns stands for not significant.

	TFW	MFW	DW	PDM	SPAD
Substrate (S)	*	*	ns	***	ns
Position (P)	***	***	*	**	ns
S x P	**	**	*	ns	*

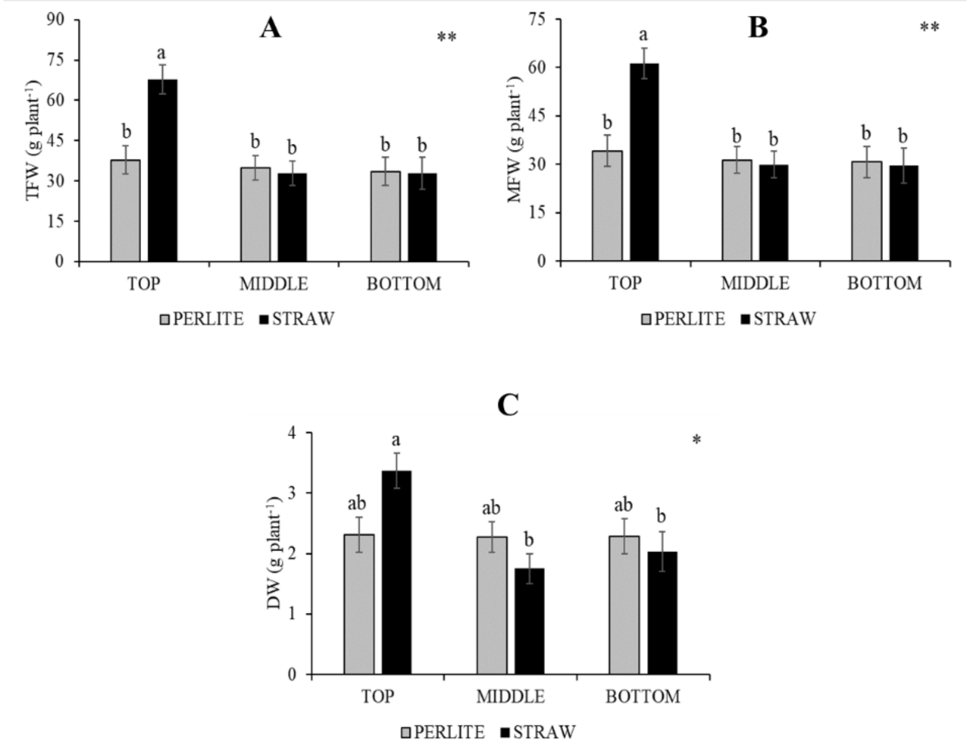

Figure 1 Interactions of growing substrate and plant position for total fresh weight (A) marketable fresh weight (B), and dry weight (C). Different letters indicate significant difference at two-way ANOVA. Vertical bars represent standard error.

The highest total and marketable plant weight was observed for plants at the top of the system when grown in the carbonized straw, but it rapidly declined moving through the middle and bottom part of the system (Figure 1A, 1B). Such behavior was previously observed by Michelon et al. (2020) in plant grown on carbonized rice hulls. We argue that the differences observed are rather determined by a different water status that is a function of the plant position. Notably, in the present study PDM was affected by the plant position, increasing when moving from the top to the bottom of the system (Figure 2A). Notoriously, dry matter is inversely correlated with water availability in root zone (Kurunc 2021), suggesting that the substrate may have impeded the gravitational flow of the nutrient solution. This could also explain the lower leaf temperature observed by Michelon et al. (2020) in the upper part of the system, as the plants in a better water status exhibits reduced leaf temperature due to transpiration process (Adeyemi et al., 2018).

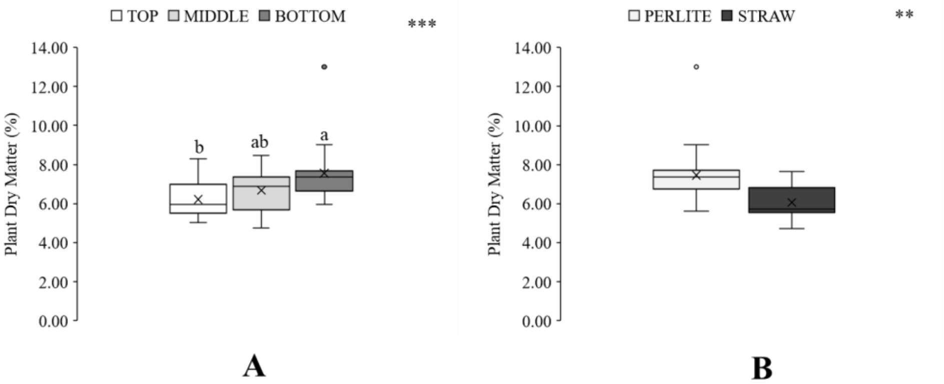

Figure 2 Main effect of plant position in the system (A) and of the growing substrate (B) in plant dry matter content. Different letters indicate significant difference at Kruskal-Wallis test.

However, plants grown in perlite maintained the yield independently to their position in the system (Figure 1), despite their dry matter was negatively affected (Figure 2A). Carbon-rich materials, as wheat straw, are known to be characterized by a high water retention when they are charred in biochar (Razzaghi et al., 2020). It is advanced that the drainage ability of carbonized straw is more limited than perlite, resulting in more evident discrepancies in plant yield as a function of the position (Figure 1A and 1B). Also it results in a generally lower PDM of charred straw in comparison to perlite (Figure 2B). Differences in drainage properties were visually evident between carbonized straw and perlite during the implementation of the hydroponic system. Notably, issues of occlusion were observed in the drainage at the end of the bottle lines filled with straw, highlighting a substantial contrast with perlite. Furthermore, when the when dry weight is considered (Figure 1C), all the plants grown in perlite obtained yield statistically comparable with plants grown in straw in the top of the system. This is justified by the higher dry matter of plants grown in perlite as shown in Figure 2B, thus compensating for the lower fresh weight observed in Figure 1A and 1B. However, charred straw is a promising low-cost substrate that can surrogate the commercial perlite in simplified hydroponics in Fernena. Improvements in its draining capacity are however needed to boost the yield also in the bottom part of the system.

Potential use of SPAD in simplified hydroponics

The highest SPAD value observed for plants grown in straw in the top of the system (Figure 3A) potentially confirm their improved nutritional status, although significant differences are detected only with straw treatment plants grown in the middle part of the system. A reduced drainage in charred straw may determine salts accumulation in root zone (Na^+ and Cl^{-1}) at the bottom of the system (Massa et al., 2010) then limiting water absorption inducing nutritional deficiency (Savvas et al., 2005). However, further assessments are required to verify such hypothesis.

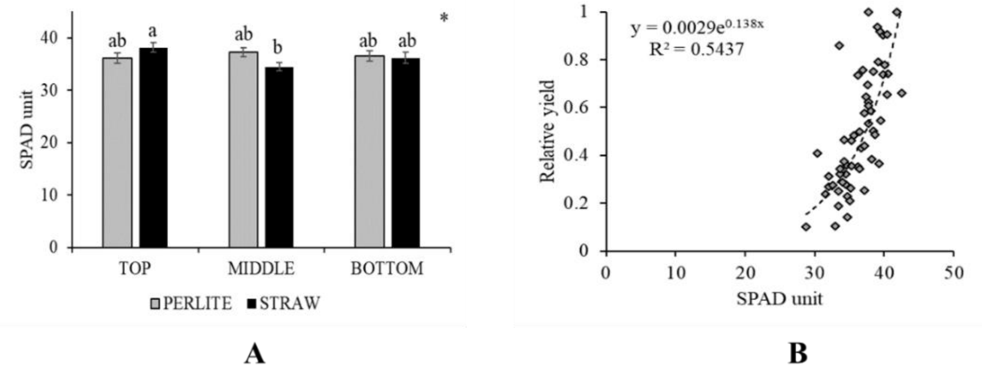

Figure 3 Interaction of growing substrate and plant position in SPAD measurements (A), and non-linear relationship between relative yield and SPAD unit measured at harvest (B). Different letters indicate significant difference at two-way ANOVA. Vertical bars represent standard errors.

The use of SPAD does not rely only to nutritional status monitoring, as it has been used to monitor and guide the dynamic nitrogen fertilization in open field crops to maximize the yield (Gianquinto et al., 2004). The feasibility of optical sensors use from smallholders has been formerly addressed by literature although it was so far mostly limited to field crops (Michelon et al., 2020), while limited applications are available for simplified hydroponic systems. In the present experiment relative yield was correlated with SPAD value according an exponential function (Figure 3B). Although the correlation is significant (p<0.05), a saturation effect seems to occur at SPAD values close to 40. This result suggests that SPAD have potential to be used as tool for estimating the yield of lettuce. However, saturation effect occurs at sub-optimal yield level, approximately close to 60% of the maximum yield. This limitation makes the use of SPAD less applicable for guiding agronomical management to maximize the yield. Further studies are required to assess the phenological stages more relevant for SPAD monitoring and circumvent saturation effect. The development and integration of cheaper instruments to monitor the crop status is highly recommended for smallholder agriculture.

Yield performance and water use efficiency of the hydroponic system

The yield performances per m^{-2} of the carbonized straw are rather low as compared with the yield obtained by Michelon et al. (2020). In the charred straw the marketable yield was 1.78 kg m^{-2} in the top of the system and 0.86 kg m^{-2} for the medium and bottom positions (1.11 kg m^{-2} on average), while 3 kg m^{-2} were reached by Michelon et al. (2020) in a warm and arid environment. Such discrepancies are probably determined by the different environmental conditions, although the too short growing season during autumn contributed to limit the yield in our experiment. Furthermore, the presence of shading elements nearby the hydroponic system further reduced the solar radiation for plants. However, lettuce production in a hydroponic system is virtually feasible during all the year (Martinez-Mate et al., 2018). In Fernana, months available for lettuce cultivation are individuated as those months where average minimum temperature is above the base temperature of lettuce (5 °C, Incrocci et al., 2006). Consequently December, January and February were not considered as the air temperature falls below this threshold. Considering the average length of the growing season of 45 days used in the experiment, around 6 cultivation cycle can be realized along the year. Thus, around 7 kg m^{-2} $year^{-1}$ can be reached using simplified hydroponic system in Fernena. However, this productivity is likely underestimated as in warmer season the lettuce growth would be accelerated by the higher temperature. Further studies on lettuce productivity in spring-summer season a required for a more accurate analysis. The Italian Guidelines for a healthy diet (NUTRIZIONE, 2018) recommend a consumption of leafy vegetable of about 200 g day^{-1} for an average caloric requirement of 2000 kcal day^{-1}. Therefore, 6 m^2 would be needed to satisfy the recommended lettuce requirements of an average human during the period when lettuce cultivation is feasible. The yield obtained in the current experiment is limited even if compared with the on-soil lettuce productivity in Tunisia (2.7–4.5 kg m^{-2} per growing cycle, R'him et al., 2022; Nagaz et al., 2013), and strategies for boosting yield in simplified hydroponic systems are warranted.

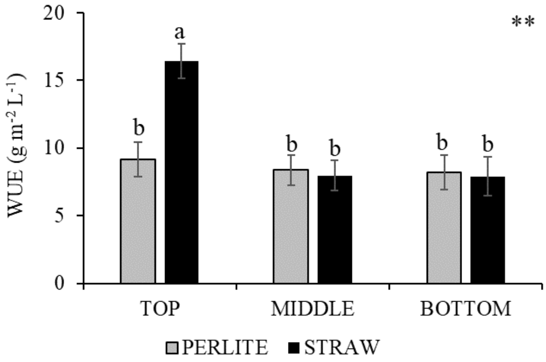

Figure 4 Interaction of growing substrate and plant position in the system for water use efficiency (WUE). Different letters indicate significant difference at two-way ANOVA. Vertical bars represent standard errors.

A total water consumption of 2.4 L $m^{-2}d^{-1}$ was observed, which was comparable with those reported by Michelon et al. (2020) in a similar system. The trend of Water Use Efficiency (WUE, Figure 4) observed in the experiment reflected the limited yield obtained in the system. When plants were grown in straw in the upper part of the system, the highest WUE was observed (16.4 g m^{-2} L^{-1}, Figure 4). This WUE was comparable with the WUE commonly reached for on-soil lettuce cultivation (13.3 g m^{-2} L^{-1}, Martinez-Mate et al., 2018), but lower as compared with the WUE reached in a similar hydroponic system (up to 45 g L^{-1} m^{-2} by Michelon et al., 2020). To verify whether the crop was grown under water stress conditions, the ET_c was calculated considering the Kc recommended by FAO (Allen et al., 1998), resulting in an average daily consumption of 1.2 L $m^{-2}d^{-1}$. The seemingly high-water supply in the experiment at 2.4 L m^{-2} d^{-1}, double the recommended computed ETc, gains perspective when considering the elevated plant density used in this study (29 plants m^{-2}). This plant density is more than two-fold higher than the typical density observed in conventional soil-based lettuce cultivation (12 plants m^{-2}), which probably increased crop transpiration above estimated values because of the higher canopy cover area. Therefore, the water consumption becomes more comparable when the plant consumption is considered (measured 0.08 L d^{-1} $plant^{-1}$ vs estimated 0.10 L d^{-1} $plant^{-1}$), suggesting that water was not a limited resource in the experiment. The solar radiation availability was likely identified as a limiting factor, particularly due to shading elements in close proximity to the hydroponic system. This further mitigated the already reduced levels of solar radiation characteristic of the autumnal season. Strategies to increase crop productivity in simplified hydroponics in Northern Tunisia are proposed:

a) Increase radiation availability for autumnal-winter growing season, or in radiation-limited conditions (e.g., use of white reflective elements in the system)
b) Increase growing cycle during autumnal environment to 60 days
c) Increase drainage properties of charred straw integrating coarse materials

CONCLUSIONS

The utilization of carbonized straw as a cost-effective substrate in simplified hydroponics presents a promising application in line with the principles of circular economy. The superior yield and WUE observed in plants grown in straw in the upper part of the system, outperforming perlite, highlight the potential of this alternative substrate. However, a decline in yield was noted as one moved through the bottom part of the hydroponic system, likely attributed to the reduced drainage capacity of the charred straw. The incorporation of coarse material in the charred straw is a strategy recommended that could boost the crop yield also in the bottom part of the system. Yield performances of the hydroponic system were below the yield observed in literature for similar systems or even for soil cultivation. Such discrepancies are mainly determined by the short growing cycle in relation to the autumnal season, as well as the reduced solar radiation due to nearby shading elements. Strategies to increase the system productivity were proposed. Additionally, the positive correlation observed between SPAD values and plant weight suggests the potential integration of optical sensors in managing simplified hydroponic systems. However, the saturation effect observed in SPAD values limits the yield prediction, emphasizing the need for more research. The development of low-cost sensors is desirable to enhance the accessibility of precision tools by smallholders.

Aknowledgment

The research leading to this publication has received funding from the European Union’s Horizon 2020 research and innovation programme under grant agreement no. 862802. The publication reflects the author’s views. The Research Executive Agency (REA) is not liable for any use that may be made of the information contained therein.

Literature cited

Adeyemi, O., Grove, I., Peets, S., Domun, Y., and Norton, T. (2018). Dynamic modelling of the baseline temperatures for computation of the crop water stress index (CWSI) of a greenhouse cultivated lettuce crop. Comput. Electron. Agric. 153, 102-114.

Allen, R.G., Pereira, L.S., Raes, D., and Smith, M. (1998). Crop evapotranspiration-Guidelines for computing crop water requirements-FAO Irrigation and drainage paper 56. Fao, Rome, 300(9), D05109.

Dakhlaoui, H., Seibert, J., and Hakala, K. (2020). Sensitivity of discharge projections to potential evapotranspiration estimation in Northern Tunisia. Reg. Environ. Change, 20, 1-12.

Gianquinto, G., Goffart, J.P., Olivier, M., Guarda, G., Colauzzi, M., Dalla Costa, L., Delle Vedove, G., Vos, J., and Mackerron, D.K.L. (2004). The use of hand-held chlorophyll meters as a tool to assess the nitrogen status and to guide nitrogen fertilization of potato crop. Potato Res., 47, 35-80.

Hargreaves, G.H., and Samani, Z.A. (1985). Reference crop evapotranspiration from temperature. Appl Eng. Agr., 1(2), 96-99.

Incrocci, L., Fila, G., Bellocchi, G., Pardossi, A., Campiotti, C. A., and Balducchi, R. (2006). Soil-less indoor-grown lettuce (Lactuca sativa L.): Approaching the modelling task. Environ. Model Softw., 21(1), 121-126.

Jabloun, M.D., and Sahli, A. (2008). Evaluation of FAO-56 methodology for estimating reference evapotranspiration using limited climatic data: Application to Tunisia. Agric. Water Manag., 95(6), 707-715.

Kurunc, A. (2021). Effects of water and salinity stresses on growth, yield, and water use of iceberg lettuce. K. Sci. Food Agric., 101(13), 5688-5696

Martinez-Mate, M.A., Martin-Gorriz, B., Martínez-Alvarez, V., Soto-García, M., and Maestre-Valero, J. F. (2018). Hydroponic system and desalinated seawater as an alternative farm-productive proposal in water scarcity areas: Energy and greenhouse gas emissions analysis of lettuce production in southeast Spain. J. Clean. Prod., 172, 1298-1310.

Massa, D., Incrocci, L., Maggini, R., Carmassi, G., Campiotti, C. A., and Pardossi, A. (2010). Strategies to decrease water drainage and nitrate emission from soilless cultures of greenhouse tomato. Agric. Water Manag, *97*(7), 971-980.

Michelon, N., Pennisi, G., Myint, N.O., Dall'Olio, G., Batista, L. P., Salviano, A.A.C., Gruda, N.S., Orsini, F., and Gianquinto, G. (2020). Strategies for improved yield and water use efficiency of lettuce (Lactuca sativa L.) through simplified soilless cultivation under semi-arid climate. Agronomy, 10(9), 1379.

Michelon, N., Pennisi, G., Myint, N.O., Orsini, F., and Gianquinto, G. (2021). Optimization of Substrate and Nutrient Solution Strength for Lettuce and Chinese Cabbage Seedling Production in the Semi-Arid Environment of Central Myanmar. Horticulture, 7(4), 64.

Nagaz, K., Mokh, F.E., Masmoudi, M.M., and Mechlia, N.B. (2013). Soil salinity, yield and water productivity of lettuce under irrigation regimes with saline water in arid conditions of Tunisia. Int. J. Agron. Plant Prod., 4(5), 892-900.

NUTRIZIONE, C.D.R.A.E. (2018). Linee Guida Per Una Sana Alimentazione. Centro di Ricerca Alimenti e Nutrizione: Roma, Italy.

Orsini, F., Kahane, R., Nono-Womdim, R., and Gianquinto, G. (2013). Urban agriculture in the developing world: a review. Agron. Sustain. Dev., 33, 695-720.

Orsini, F., Mezzetti, M., Fecondini, M., Michelon, N., and Gianquinto, G. (2009). Simplified substrate soilless culture for vegetable production in Trujillo, Peru. Paper presented at: II International Conference on Landscape and Urban Horticulture 881 (pp. 163-167).

Pechan, P.M., Obster, F., Marchioro, L., and Bohle, H. (2023). Climate change impact on fruit farm operations in Chile and Tunisia. agriRxiv, 20230025166

Razzaghi, F., Obour, P.B., and Arthur, E. (2020). Does biochar improve soil water retention? A systematic review and meta-analysis. Geoderma, 361, 114055.

R'him, T., Romdhane, L., Nicoletto, C., Tlili, I., Ilahy, R., Ghannem, S., and Radhouane, L. (2022). Changes in morphological and physiological parameters affecting lettuce cultivars due to nitrogen fertilizer in greenhouse tunnel. J. Post harvest Technol., 10(1), 19-34.

Savvas, D., Meletiou, G., Margariti, S., Tsirogiannis, I., and Kotsiras, A. (2005). Modeling the relationship between water uptake by cucumber and NaCl accumulation in a closed hydroponic system. HortScience, 40(3), 802-807.