Application of LCA methodology to a Recirculating Aquaponics System (RAS) prototype

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Abstract

In the current scenario of increasing urbanization and food consumption, aquaponic systems are generally regarded as sustainable food production systems. However, its environmental burdens (energy consumption, materials, etc.) were not deeply investigated yet. To assess aquaponics environmental performance systematically, it is important to take the whole life cycle into account. The aim of this study was to identify and to evaluate the environmental impact of a Recirculating aquaponics system (RAS) prototype, using a life cycle assessment (LCA) methodology. Leafy vegetables [i.e. lettuce (*Lactuca sativa* L.), curly endive (*Cichorium endivia* var. *crispum*) and escarole endive (*Chicorium endivia* var. *latifolia*)] were grown on floating rafts in combination with tilapia (*Oreochromis niloticus* L.) at two different lighting regimes (i.e. natural sunlight and natural sunlight integrated with LED supplemental light). Our LCA analysis included four different steps: 1) Definition of the goal and scope of the study; 2) Life cycle inventory (data collection); 3) Life cycle impact assessment (data translation into environmental indicators); 4) Interpretation and analysis of the results. Our preliminary results suggest that electricity was the main contributing factor to environmental impact, especially with supplemental light. This LCA study can be useful for providing the groundwork to reduce the potential environmental impact of aquaponics systems.

Keywords: urban agriculture, environmental impact assessment, sustainable food, energy saving

INTRODUCTION

In a context characterized by the climate change and ecosystem degradation due to intensive agricultural practices, growing world population, urbanization and the consequent increase of the world's food demand, it is of critical importance to find more sustainable strategies to produce food in urban areas. In recent years, interest in urban agriculture (UA) has increased both as instrument of support to environmental sustainability of urban areas (green infrastructures, Coppola et al., 2019) and as a tool to foster social and economic urban development (Martellozzo et al., 2014; Khan et al., 2020). Due to its multi-functionality UA plays a key role in supplying food systems in cities, increasing food security and allowing not only a biodiversity preservation, but also a safer use of urban spaces and a proper soil and water management (Mougeot, 2000). In particular urban horticulture, as food production and related short-chain consumption systems, has experienced an unexpected growth, through the developed synergies between the efforts towards the re-valorization of traditional crops, and the increased application of innovative and sustainable farming models and cultivation techniques (vertical farming, soilless cultivation systems, etc.) that can counteract adverse environmental impact of food production, such as land and water consumption, intensive use of pesticides and chemical fertilizers (Khan et al., 2020; Buscaroli et al., 2021). Among these systems, aquaponics food production, by combining aquaculture and hydroponic vegetable cultivation, has been already confirmed as a high water and nutrient use efficiency system (Calone et al., 2019; Sanyé-Mengual et al., 2019).

Life Cycle Assessment (LCA) is a tool used to evaluate the environmental impact of a product, process, or activity through its life cycle; previous studies applied LCA methodology to food production systems, including aquaponics (Cohen et al., 2018; Forchino et al., 2017) that as integrated production system was proven to be more sustainable and economically valuable than separate aquaculture and plant production (Greenfeld et al., 2021) .In the present study, a LCA analysis was performed on a aquaponic system in which fish production was combined with multiple vegetable species cultivation, grown under natural light or integrated daily light treatments, in order to identify and to quantify their environmental burdens and to evaluate the potential threshold of sustainability that allows to increase yield under supplemental lighting (Modarelli et al. in press). Indeed, final aim of the work was to model a commercial-scale aquaponics system allowing both to optimizing yield and minimizing environmental impact.

MATERIALS AND METHODS

System description and experimental trials

A Recirculating Aquaponics System (RAS) prototype located in a 250 m^2 cold greenhouse at the CAISIAL research station, Department of Agricultural Sciences of the University of Naples Federico II, consisted in 4 fish tanks (2800 L/each) and 4 m^2 floating raft bed. Moreover, the system was equipped with a 800 L super bead system for mechanical and biological filtration, 400 L trickling filter, and 40 W UV sterilization unit. Finally a pump recirculated the water constantly and its temperature was controlled (Figure 1).

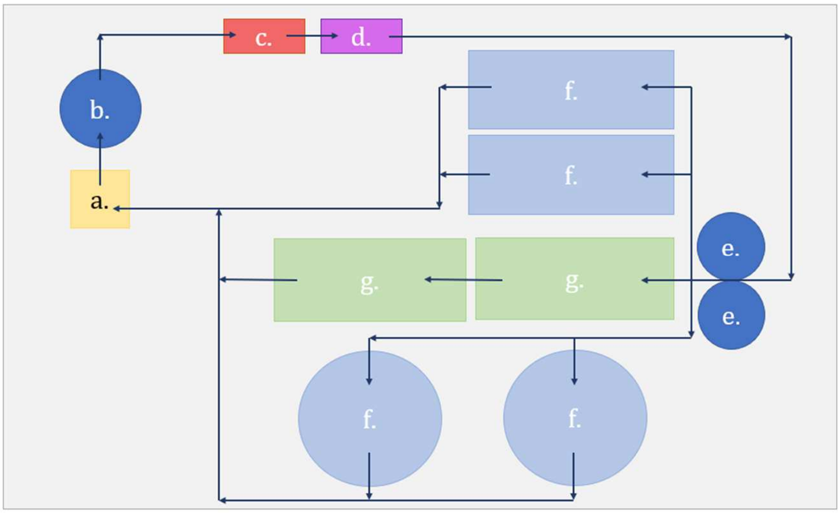

Figure 1. RAS prototype lay-out. From the upper left corner follows: a. pump; b. superbead biofilter; c. water temperature control unit; d. UV sterilization unit; e. trickling biofilter; f. fish rearing tanks, and g. floating raft unit. Arrows indicate water recirculation system.

Three cultivation cycles were conducted from December 2020 to May 2021. Leafy vegetables including lettuce (*Lactuca sativa* L. cv. Meraviglia d´inverno, L), escarole endive (*Chicorium endivia* var *latifolia* cv. Bionda a cuore pieno, EE), and curly endive (*Cichorium endivia* var *crispum* cv. De Louvriers, CE) were grow on floating raft bed in the RAS in combination with Nile tilapia (*Oreochromis niloticus* L.). The first cycle included the three species, whereas in the second and the third ones only L and CE were grown. . In particular, plant density was respectively of 25, 20 and 20 plant/m^2 and the plants were harvested after 56, 27 and 24 days (for the first, second and third cultivation cycle respectively). All the experiments were conducted growing plants under natural sunlight conditions (as control) or natural sunlight conditions integrated with 16 hours (6:00-22:00) of supplemental light provided by white LED (Hortimol TLed 40W Full Spectrum FSG, The Netherlands), at an average photosynthetic photon flux density (PPFD) of 173.5 ± 6.2 µmol.m^{-2}.s^{-1} guaranteeing a minimum daily light integral (DLI) of 10.0 ± 0.4 mol m^{-2} d^{-1}. The light spectral composition is reported in Figure 2. Water temperature was set to 23°C, pH and electrical conductivity (EC) were monitored daily over the periods of cultivation and averaged 7.0 and 850 µS cm^{-1} (over the three cycles), respectively.

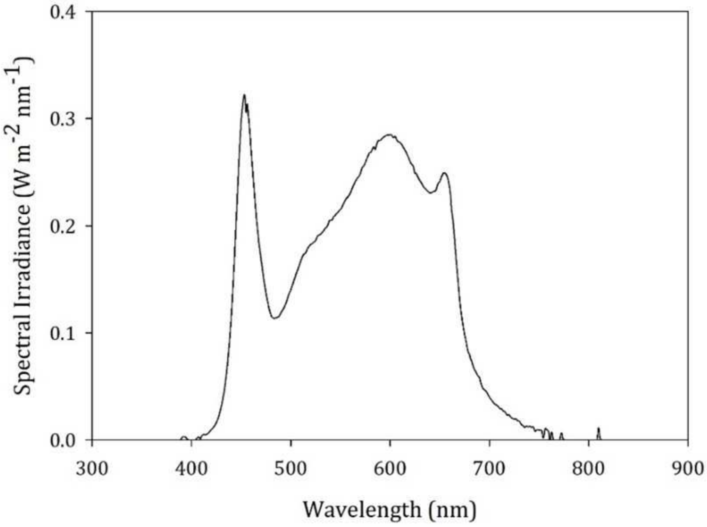

Figure 2. Spectral irradiance distribution (W m^{-2} nm^{-1}) of the white LED (Hortimol TLed 40W Full Spectrum FSG, The Netherlands). The spectra was obtained with a portable spectral light meter (MSC15, Gigahertz-Optik GmbH, Türkenfeld, Germany)

Methodology

According to the International Standard Organization definition (ISO 14040), LCA comprises 4 different steps: (i) Goal and Scope definition, (ii) Life Cycle Inventory analysis (LCI), (iii) Life Cycle Impact Assessment (LCIA), and (iv) interpretation of the results (Baldo et al., 2005).

The system boundaries were “cradle-to-gate”, therefore post harvested processes (e.g. packaging, transportation, distribution and use) were not included in the system boundaries. The functional unit (FU) of the assessment was defined as 1 kilogram (kg) of leafy vegetables produced annually; live-weight fish was considered as a coproduct.

RESULTS AND DISCUSSION

Thanks to the nitrate-rich water, leafy vegetables are easy to grow crop in aquaponics systems. However, crop production and performance may vary among species, variety, and even seasons. In our growing conditions, the yield produced were different depending on the species and on the length of the cultivation cycles (Table 1).

In particular, the three species in the first trial showed morpho-physiological differences (Modarelli et al., in press), despite the similar yield under control conditions, with lettuce plants accumulating a higher dry matter content than endives. Generally, a DLI of 17 mol m^{-2} d^{-1} is suggested when lettuce is grown under controlled environment, and a minimum DLI of 10 mol m^{-2} d^{-1} is recommended in the winter period (Pennisi et al., 2020) There are no literature information on endives DLI requirements currently. In our trials, as a result of supplying plants with a LED light DLI of 10 mol m^{-2} d^{-1} under a 16 hours fixed photoperiod, plant growth was enhanced in all the species with different adaptation mechanisms. Indeed, IL promoted plant growth in the endives, by increasing leaf number, while it increased total leaf area in L. In both cases fresh and dry biomass increased compared to NL plants, likely for the higher plant light interception (Modarelli et al., in press).

Table 1. .Total biomass harvested per species (lettuce, L; escarole endive, EE; curly endive, CE) per unit area at the end of the cultivation cycles in a coupled RAS prototype, under natural sunlight (NO LED) or supplemental LED light conditions (LED). Different letters indicate significant differences at Tukey HSD post-hoc ($P<0.05$)

	Plant density (n m^{-2})	L ($kg\ m^{-2}$)	EE ($kg\ m^{-2}$)	CE ($kg\ m^{-2}$)
1st trial	25			
NO LED		1.40 b	1.05 b	1.22 b
LED		3.31 a	3.29 a	5.68 a
2nd trial	20			
NO LED		3.53 a	-	3.67 b
LED		3.98 a	-	5.57 a
3rd trial	20			
NO LED		4.34 b	-	2.87 b
LED		5.97 a	-	4.88 a

On the base of the experimental trials carried out in the RAS system previously described, it was modeled a commercial-scale aquaponics system in which growth density was defined at 22 plant/m^2 (as average growth density of three cultivation cycles) on a surface area of 200 m^2 with natural sunlight (NO LED system) and of 200 m^2 with natural sunlight integrated with supplemental light (LED system). The LCA analysis was performed on a potentially covered time period of one year .

Life cycle inventory (LCI)

In this cradle-to-gate analysis, production of vegetables and fish are considered as the output of the system; fingerlings, seeds, water, electricity, and fish food are considered as the input of the system. These primary data were collected on experimental site during the setup steps (Table 2).

Table 2. Input and output of the two aquaponics system models obtained from the inventory analysis referred to the Functional Unit selected.

INPUT	**Quantity**	**Unit/year**
Fingerlings	58	kg
Seeds	110000	Seed no.
Water consumption	151,	CM
Electricity for UVC	481	KW
Electricity for heating water (inverter)	5400	KW
Electricity for pumps (air)	7800	KW
Electricity for pumping (water)	4380	KW
Electricity for light*	396172,8	KW
Soybean meal	88	kg
Wheat meal	106,9	kg
Fish meal	1324	kg
Rice meal	109,1	kg
Wheat bran	218,3	kg
Tapioca starch	43,6	kg
Fish oil	14,3	kg
OUTPUT		
Leafy vegetables	12124	kg
Tilapia	564,1	kg

Life cycle impact assessment (LCIA)

The CML-IA database, the basaline for characterisation factors for life cycle impact assessment proposed by Leiden University (Bicer et al., 2016) was used to estimate the following impact categories: Photochemical oxidation (PO, Kg C_2H_4 eq), Human toxicity potential (HTP, Kg 1,4 -– DB), Global warming potential (GWP, Kg CO_2 eq), Abiotic depletion (fossil fuels) (AD, MJ), Ozone layer depletion (ODP, Kg CFC – 11 eq), Fresh water aquatic ecotoxicity (FWE, Kg 1,4 – DB), Eutrophication potential (EP, Kg PO_4^{3-} eq), Marine aquatic ecotoxicity (MAE, Kg 1,,4 – DB), Acidification potential (AP, Kg SO_2 eq), and Terrestrial ecotoxicity (TE, Kg 1,4 – DB). Calculation were performed by means of OpenLCA software version 1.6.

Table 4. Quantitative results of the two aquaponics system for the impact categories considered (Source: Software OpenLCA).

Impact Category	Impact results (NO LED)	Impact results (LED)	Unit
Photochemical Oxidation			
Electricity	9.91E+00	0.00	Kg C_2H_4 eq
Fish Food	3.28E-01	-	Kg C_2H_4 eq
Human Toxicity Potential			
Electricity	0.28	6.30	Kg 1,4 - DB
Fish Food	-	-	Kg 1,4 - DB
Global Warming Potential			
Electricity	0.55	12.50	Kg CO_2 eq
Fish Food	0.02	-	Kg CO_2 eq
Abiotic Depletion (Fossil fuels)			
Electricity	3.65	84	MJ
Fish Food	0.29	-	MJ
Ozone Layer Depletion			
Electricity	5.70E-03	1.31E-01	Kg CFC – 11 eq
Fish Food	2.80E-04	-	Kg CFC – 11 eq
Fresh Water aquatic			
Electricity	0.38	9	Kg 1,4 - DB
Fish Food	-	-	Kg 1,4 - DB
Ecotoxicity			
Electricity	0.37	9	Kg 1,4 - DB
Fish Food	-	-	Kg 1,4 - DB
Eutrophication Potential			
Electricity	0.00	0.05	Kg PO_4^{3-} eq
Fish Food	11.46	-	Kg PO_4^{3-} eq
Marine Aquatic Ecotoxicity			
Electricity	1.09	2.50E+09	Kg 1,4 - DB
Fish Food	-	-	Kg 1,4 - DB
Acidification Potential			
Electricity	0.00	0.02	Kg SO_2 eq
Fish Food	4.25	0.00	Kg SO_2 eq
Terrestrial Ecotoxicity			
Electricity	0.00	-	Kg 1,4 - DB
Fish Food	14.94	-	Kg 1,4 - DB

A quantitative assessment of the two models of aquaponics system (NO LED and LED), attributed to the inputs and outputs listed above (Table 2), based on 1 kg of production of leafy vegetables over one year process, was performed.

First of all, our results (Table 4) suggest that aquaponics system model with supplemental lighting treatment (LED) contributed more to the environmental impact compared with aquaponics system model with only natural sunlight (NO LED). In particular, electricity dominated the environmental impact with the greatest contribution to the impact categories; fish food was the second highest contributor (Figure 3).

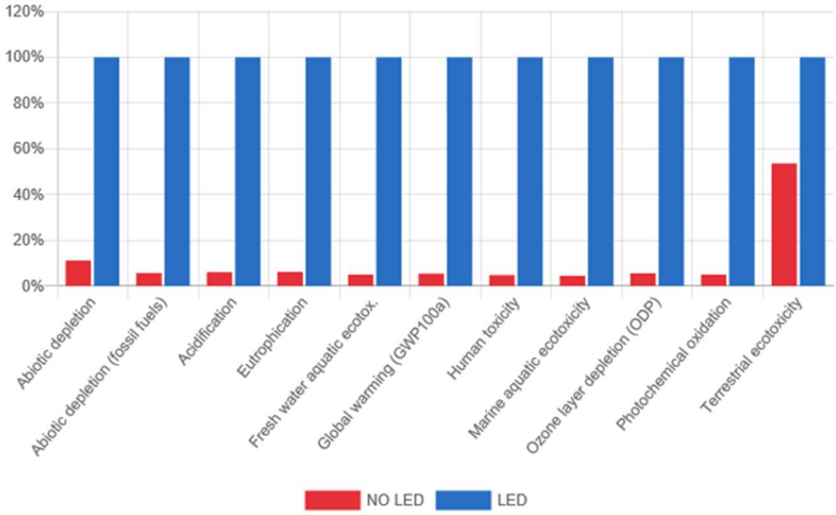

Figure 3. Indicator results of the two respective aquaponics system (NO LED and LED): for each indicator, the maximum result is set to 100 % (Source: Software OpenLCA).

Therefore, several different strategies could be adopted to reduce the energy consumption. Certainly, limiting the use of supplemental lighting treatment to the winter months in the Mediterranean area can represent a viable solution. In this way, a constant daily light integral (DLI) could be guaranteed promoting plant growth and nutrient absorption (Anderson et al., 2017). In fact, according to our agronomic results, biomass produced under supplemental lighting treatment was greater than the biomass produced under natural light only, especially during the first cultivation cycle (+ 70 %) (Figure 4).

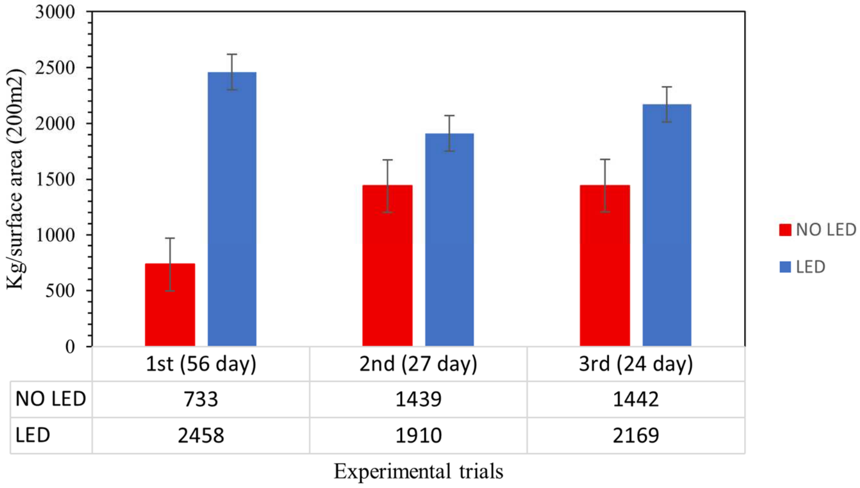

Figure 4. Total Biomass (kg/200 m^2) produced in one production cycle.

Furthermore, considering the duration of the cultivation cycle (56, 27 and 24 days for the first, second, and third experiment respectively), if we hypothesize a plant density of 25 plant/m^2 even during the spring-summer months (instead of 20 plant/m^2), the annual biomass produced would increase. Therefore, our findings support the hypothesis of limiting the use of supplemental light to the winter months as increasing density and reduction of cultivation cycles could guarantee a production of biomass that would not justify its use.

On the other hand, also the use of renewable energy sources, such as energy coming from a solar energy conversion system, could represent a viable solution to reduce energy consumption (Tokunaga et al., 2015).

As regard the impacts referred to fish feed input, a sustainable option could be the introduction of additional food sources, particularly rich in protein content, that can be produced on a farm level, like microalgae (Becker, 2007) or some fast-growing aquatic plants, such as *Lemna minor* (Araceae: Lemnoidae), also known as duckweed (Hutabarat, 2019). Another option suitable for reducing the environmental impact of fish food could be the use of feed characterized by a FCR (Feed Conversion Ratio) lower than 1, as reported by Bilen et al. (2015) that recorded FCR values of 0.83 and 0.94. Improved farming practice and feeding strategies could reduce nitrogen and phosphorus emission due to feed amounts not ingested (Avadí et al., 2015); these suspended solids, after being removed from the system, could be managed using biological approach (e.g. vermicomposting).

CONCLUSIONS

This study provides an assessment of the main environmental impacts of a coupled RAS, with particular reference to the utilization of supplemental lighting treatments as cultivation strategy to increase the yield per year. The LCA analysis performed in this study underlined that energy consumption (especially electricity) and fish feed played a key role in terms of contribution to impacts. Therefore, the optimization of management practices should be regarded as a priority in order to reduce environmental impacts deriving from the aquaponics. Moreover, the use of LCA to model alternative scenarios may represent a useful procedure to find new technical solutions aimed at increasing the sustainability of aquaponics and to expanding this practice at a wider scale.

ACKNOLEDGMENTS

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Literature citated

Anderson, T.S., Martini, M.R., De Villiers, D., and Timmons, M.B. (2017). Growth and tissue elemental composition response of Butterhead lettuce (Lactuca sativa, cv. Flandria) to hydroponic conditions at different pH and alkalinity. *Horticulturae*, 3(3), 41 https://doi.org/10.3390/horticulturae3030041.

Avadí, A., Pelletier, N., Aubin, J., Ralite, S., Núñez, J., and Fréon, P. (2015). Comparative environmental performance of artisanal and commercial feed use in Peruvian freshwater aquaculture. *Aquac.*, 435, 52-66 https://doi.org/10.1016/j.aquaculture.2014.08.001.

Bicer, Y., Dincer, I., Zamfirescu, C., Vezina, G., and Raso, F. (2016). Comparative life cycle assessment of various ammonia production methods, *J. Clean. Prod.,* 135: 1379-1395 doi.org/10.1016/j.jclepro.2016.07.023.

Baldo, G.L., Marino, M., and Rossi, S. (2005). Analisi del ciclo di vita LCA-Materiali, prodotti, processi. Edizioni Ambiente srl, pp. 289.

Becker, E.W. (2007). Micro-algae as a source of protein. *Biotechnol. adv*, 25(2), 207-210 https://doi.org/10.1016/j.biotechadv.2006.11.002.

Bilen, S., Bilen, A.M., and Önal, U. (2015). The effects of oxygen supplementation on growth and survival of rainbow trout (*Oncorhynchus mykiss*) in different stocking densities. *Iran. J. Fish. Sci.*,14(3), 538-545.

Buscaroli, E., Braschi, I., Cirillo, C., Fargue-Lelièvre, A., Modarelli, G. C., Pennisi, G., Righini, I., Specht, K., and Orsini, F. (2021). Reviewing chemical and biological risks in urban agriculture: a comprehensive framework for food safety assessment in City Region Food Systems. *Food Control* 126, 108085

Calone, R., Pennisi, G., Morgenstern, R., Sanyé-Mengual, E., Lorleberg, W., Dapprich, P., and Gianquinto, G. (2019). Improving water management in European catfish recirculating aquaculture systems through catfish-lettuce aquaponics. *Sci. Total Environ*., 687, 759-767, https://doi.org/10.1016/j.scitotenv.2019.06.167.

Cohen, A., Malone, S., Morris, Z., Weissburg, M., and Bras, B. (2018). Combined fish and lettuce cultivation: an aquaponics life cycle assessment. *Procedia Cirp.* 69, 551-556 https://doi.org/10.1016/j.procir.2017.11.029.

Coppola, E., Rouphael, Y., De Pascale, S., Moccia, F.D., Cirillo, C. (2019). Ameliorating a complex urban ecosystem through instrumental use of softscape buffers: proposal for a green infrastructure network in the metropolitan area of Naples. *Front. Plant Sci*., 10, 410

Forchino, A.A., Lourguioui, H., Brigolin, D., and Pastres, R. (2017). Aquaponics and sustainability: The comparison of two different aquaponic techniques using the Life Cycle Assessment (LCA). *Aquacult Eng*., 77, 80-88 https://doi.org/10.1016/j.aquaeng.2017.03.002.

Greenfeld, A., Becker, N., Bornman, J. F., Spatari, S., and Angel, D. L. (2021). Monetizing environmental impact of integrated aquaponic farming compared to separate systems. *Sci. Total Environ*., *792*, 148459, https://doi.org/10.1016/j.scitotenv.2021.148459.

Hutabarat, J., Radjasa, O.K., and Herawati, V. E. (2019). Growth and nutrient value of tilapia (Oreochromis niloticus) fed with Lemna minor meal based on different fermentation time. *Aquac., Aquar., Conserv. Legis.*, 12(1), 191-200.

Khan, M.M., Akram, M.T., Janke, R., Qadri, R.W.K., Al-Sadi, A.M., and Farooque, A.A. (2020). Urban horticulture for food secure cities through and beyond COVID-19. *Sustainability*, 12(22), 9592 https://doi.org/10.3390/su12229592.

Martellozzo, F.E., Landry, J.S., Plouffe, D., Seufert, V., Rowhani, P., and Ramankutty, N. (2014). Urban agriculture: a global analysis of the space constraint to meet urban vegetable demand. *Environ. Res. Lett.*, 9(6), 064025 https://doi.org/10.1088/1748-9326/9/6/064025.

Modarelli, G.C, Vanacore, L., Langellotti, A.L., Masi, P., Cirillo, C., De Pascale, S., Rouphael, Y. Supplemental daily light integral by LED light to improve the growth of leafy vegetables in aquaponics system. ISHS VIII International Conference on Landscape and Urban Horticulturae, 15-17 December 2021, Catania (IT), Acta Hortic. (in press)

Mougeot, L. J., (2000). Urban agriculture: definition, presence, potentials and risks. Growing cities, growing food: Urban agriculture on the policy agenda,1, 42.

Pennisi, G., Pistillo, A., Orsini, F., Cellini, A., Spinelli, F., Nicola, S., et al. (2020). Optimal light intensity for sustainable water and energy use in indoor cultivation of lettuce and basil under red and blue LEDs. *Sci. Hortic*. (Amsterdam). 272, 109508. doi:10.1016/j.scienta.2020.109508.

Sanyé-Mengual, E., Secchi, M., Corrado, S., Beylot, A., and Sala, S. (2019). Assessing the decoupling of economic growth from environmental impacts in the European Union: A consumption-based approach. *J. Clean. Prod.,*236, 117535, https://doi.org/10.1016/j.jclepro.2019.07.010.

Tokunaga, K., Tamaru, C., Ako, H., and Leung, P.S. (2015). Economics of small-scale commercial aquaponics in Hawai'i. *J. World Aquacult. Soc.* 46 (1), 20–32 http://dx.doi.org/10.1111/jwas.12173.