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Articles

Yields and water use efficiency of lettuce and cherry tomatoes in urban gardens

Rendimientos y eficiencia en el uso del agua de lechuga y tomate cherry en jardines urbanos

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Abstract

Urban and peri-urban horticulture presents major challenges, such as low water and land availability for agricultural use. So far, there are no data on the amount of water needed for vegetable production in Mexico City (CDMX). Therefore, the objective of this study was to estimate the yield and water use efficiency of two representative crops in urban gardens, including romaine lettuce and cherry tomato, for 13 urban gardens in CDMX. In addition, the rainwater storage capacity was estimated using data from the closest weather station from each orchard, in order to make statements about the coverage of the water demand for the plants. Yield and water use efficiency for lettuce production ranged between 0.10 and 1.20 kg m^{-2} as well as 0.21 to 2.93 kg m^{-3} water, respectively. These indicators for the case of cherry tomato were between 0.25 and 3.40 kg m^{-2} and between 0.32 and 5.52 kg m^{-3} water, respectively. Irrigation in the urban gardens was done in an empirical way and using fresh water. It was found, in most of the cases, an excess of water supply which can be up to 0.27 and 0.4 m^3 m^{-2} for a complete growth season of lettuce and cherry tomato. The rainwater storage capacity in a year was estimated using an 80 % probability of exceedance. The accumulated rainwater storage varies from 0.261 to 0.5215 m^3 m^{-2} in the orchards, which could supply the water requirements for a complete season of lettuce (0.128 to 0.389 m^3 m^{-2}) or cherry tomato (0.145 to 0.569 m^3 m^{-2}).

Keywords: Mexico City, urban farming, rainwater, water use, megacities.

Resumen

La horticultura urbana y periurbana (HUP) presenta grandes desafíos, como la poca disponibilidad en el suministro del agua y de tierra. No existen datos sobre la cantidad de agua que se utiliza para la producción de hortalizas en la Ciudad de México (CDMX). Por lo tanto, el objetivo del presente estudio fue la estimación de los rendimientos y la productividad del agua para dos hortalizas representativas en jardines urbanos: lechuga romana y tomate cherry en 13 huertos urbanos de la CDMX. Asimismo, se estimó el volumen de agua de lluvia que se puede almacenar en cada huerto, utilizando la estación meteorológica más cercana. El rendimiento y la eficiencia del uso del agua para la producción de lechuga oscilaron entre 0.10 y 1.20 kg m^{-2}, así como de 0.21 a 2.93 kg m^{-3} de agua, respectivamente. Estos indicadores, para el caso de tomate cherry, estuvieron entre 0.25 y 3.40 kg m^{-2} y entre 0.32 y 5.52 kg m^{-3} de agua, respectivamente. El riego en los huertos se hace de manera empírica y utilizando agua potable; el exceso en el suministro de agua puede ir de 0.27 a 0.4 m^3 m^{-2} para un ciclo completo de lechuga y tomate cherry, respectivamente. Utilizando una probabilidad de excedencia del 80 %, se estimó la captación de agua de lluvia para todo el año, generando un almacenamiento acumulado entre 0.261 y 0.5215 m^3 m^{-2} en los huertos urbanos. Esta cantidad de agua podría suplir los requerimientos hídricos de lechuga (de 0.128 a 0.389 m^3 m^{-2}) o tomate cherry (de 0.145 a 0.569 m^3 m^{-2}) para un ciclo completo.

Palabras clave: Ciudad de México, agricultura urbana, agua de lluvia, uso del agua, megaciudades.

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Introduction

According to the United Nations (United Nations, Department of Economic and Social Affairs Population Division, 2019), Mexico City (CDMX) and its metropolitan area is one of the most important megacities in the world, with a population of 21 581 000 inhabitants. It has the associated problems of all big cities, including: pollution, increasing food demand, as well as reduced availability of water, land and energy (Farfan, Lohrmann, & Breyer, 2019; Lupia & Pulighe, 2015). In this context, urban and peri-urban agriculture (UPA) are alternative solution to: 1) supply fresh food in cities (Khumalo & Sibanda, 2019); 2) reduce the impact on the environment by increasing the biodiversity, mitigation of the "urban heat island effect", reducing flood risks and food miles (McEldowney, 2017); 3) be an important source of jobs and income (Aubry & Nastaran, 2019). Urban and peri-urban horticulture (UPH) is a part of the UPA that is focused on the production of vegetables, as well as ornamental plants grown within and around the cities. The expansion of the UPH is limited by the specific plant requirements, as well as by a general water and land accessibility in the cities (Li, Wang, Liu, & Zhu, 2019; Pulighe & Lupia, 2019). The area available for agricultural and horticultural use, as well as climate conditions in the cities are generally not appropriate, which limits the range of crops that can be grown. In tropical and subtropical areas of developing countries, the amount of water required to grow tomato is between 400-800 L m^{-2} for the entire season (van Veenhuizen, 2006) and yield can be up to 50 kg of fresh produce per square meter per year, which is mostly depending on the technology applied (FAO, 2001). Generally, UPH uses fresh water supply for crop irrigation, increasing the pressure of this resource already limited in the urban centers. Hence, it is necessary to look for reliable water sources in quantity and quality (Amos, Rahman, Karim, & Gathenya, 2018).

According to Garcia (2018) CDMX rainwater contains microorganisms, aluminium, lead, zinc, mercury, arsenic and nickel, among others, and can only be used for tasks, such as washing cars and clothes or for irrigation, but not as drinking water for humans. Therefore, rainwater is an alternative water source for irrigation of plants, which can be stored in the structure and architecture of the building (Skara *et al*., 2020). Particularly, in Mexico there are few studies in terms of using rainwater storage to supply water requirements for the production of vegetables in the cities (McDougall, Kristiansen, & Rader, 2019).

Some of the most cultivated vegetables in urban gardens are lettuce and tomato plants, their consumption per person per year in Mexico is 2.5 kg (Bobadilla, Rivera, & Del-Moral, 2010) and 13.8 kg, respectively (SIAP, 2016). In 2018, tomato production was 1 948 million tons with an average yield of 76.8 tons ha^{-1}, being the most important vegetable in Mexico. As such, tomatoes are produced on an area of 49 415.72 ha and brings to Mexico 31 150 million pesos. In the same year, lettuce production was 486 439 tons with an average yield of 23.7 $t \cdot ha^{-1}$ (SIAP, 2019). Given the current importance of urban horticulture worldwide, as well as the problems on water availability for horticultural usage, the objective of this work was to estimate yields and water use efficiencies for lettuce and cherry tomato produced in urban gardens in CDMX. Furthermore, the water requirements of these crops and the availability of the site-specific rainwater volume to match the water requirements will be evaluated.

Materials and methods

Urban gardens and crops studied

Out of a total of 16 counties in CDMX, 13 urban gardens were selected, which were evaluated during a production cycle of romaine lettuce (*Lactuca sativa L.*) and cherry tomato (*Solanum Lycopersicum cerasiforme*) in 2018. Figure 1 shows a spatial distribution of the selected orchards including the weather stations used for estimation of the rainwater storage.

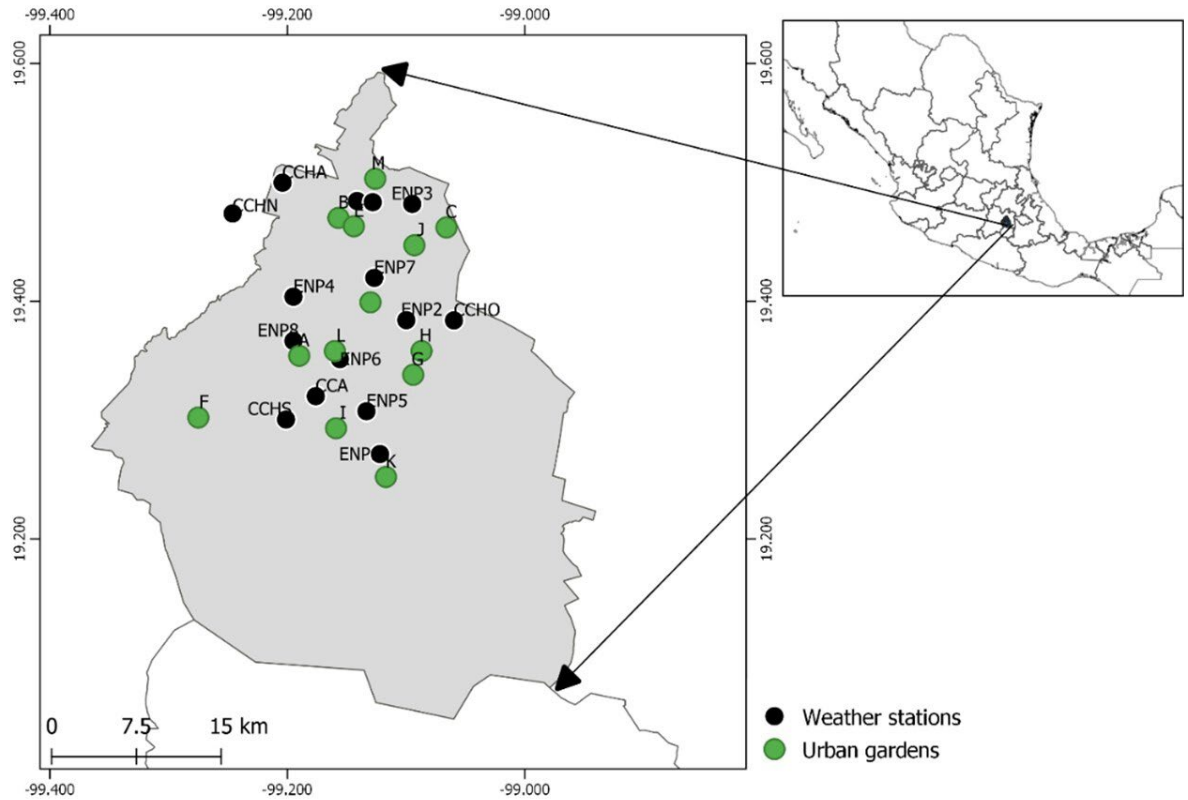

Figure 1. Geographical location of urban gardens and weather stations used in this study.

Most of the urban gardens are dedicated to teaching and demonstration of urban agriculture and their production is for self-consumption, or sold to the neighbors and local markets. Urban garden A is located in a hospital; B and C are community gardens dedicated to teaching and recovering public spaces; D is for the integration of older adults into productive activities and recreation; F, G are private greenhouse gardens; I is a private rooftop orchard; J and M are private orchards; E, H and K are managed by researchers from the Metropolitan Autonomous University; L is dedicated to employee’s recreation of the Zimat company.

Table 1 presents the characteristics of the urban gardens with the associated identification number (ID) and the weather stations (WE) located near the gardens.

Table 1. Characteristics of the 13 urban gardens analyzed in Mexico City.

Garden	ID	County	Type of Urban garden	Irrigation	Texture	AWSC	P_{soil}	WE
Asilo Mundet	A	Alvaro Obregón	Open field/pots	Manual	Light	60	40	ENP8
Azcapotzalco	B	Azcapotzalco	Open field/soil	Manual	Heavy	200	100	CCHV
Bosques de Aragón	C	Bosques de Aragón	Greenhouse/pots	Drip	Medium	290	30	ENP3
Iztacalco	D	Iztacalco	Open field/soil	Manual	Medium	290	80	ENP7
Los niños	E	Cuauhtémoc	Open field/soil	Manual	Medium	290	100	ENP9
Magdalena Contreras	F	Magdalena Contreras	Greenhouse/soil	Drip	Heavy	200	60	CCHS
Matlaloc	G	Iztapalapa	Greenhouse/soil	Drip	Medium	290	50	ENP2
San Miguel	H	Iztapalapa	Open field/soil	Manual	Medium	290	50	CCHO
Tlalpan	I	Tlalpan	Rooftop/ pots	Manual	Light	60	30	CCA
Venustiano Carranza	J	Venustiano Carranza	Rooftop/ pots	Manual	Light	60	20	ENP3
Xochimilco	K	Xochimilco	Open field/soil	Manual	Heavy	200	80	ENP1
Zimat	L	Coyoacan	Rooftop/ pots	Manual	Heavy	200	40	ENP6
Tonantzin	M	Gustavo A. Madero	Open field/soil	Manual	Medium	290	100	ENP9

AWSC = Available Water Storage Capacity of the soil (mm water m soil^{-1}) (Smith, 1992); P_{soil} = Soil rooting depth (cm); WE = Weather station.

The experimental area in each garden was 1 m^2 per each crop, a soil sample of 0.5 kg was taken in each urban garden at the depth of 20 cm and stored in polyethylene bags at 4°C until their analysis in the Laboratorio Nacional de Investigación y Servicio Agroalimentario y Forestal at the Universidad Autónoma Chapingo. After the identification of the soil texture, the CROPWAT program developed by FAO (Smith, 1992) was used to determine the available water storage capacity of the soil (AWSC) (mm water m $soil^{-1}$).

Lettuce and cherry tomato seeds were sown on April 1, 2018, into a soil prepared with compost in relation 1:1 and ultrasol fertilizer (15-30-15). Both vegetables were transplanted on April 30, 2018 in pots for sites A, C, I, J, L and directly into the soil for the rest of the gardens, at a density of 3 plants m^{-2}. The cherry tomato plants were left with three main stems with 3 bunches each. The crops were harvested on July 4 and August 23, 2018, 95 and 143 days after sowing (DAS), for lettuce and cherry tomatoes, respectively. The water applied to the crops and the harvested product were measured in each urban garden to calculate yields (Y, kg m^{-2}) and water use efficiency (WUE, kg m^{-3}) for the production cycle, following the expression cited by Salazar, Rojano and López (2014):

$$WUE = \frac{Production\ (kg)}{Water\ use\ (m^3)} \tag{1}$$

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Soil water balance in the urban gardens

The deficit of water in the soil is a limiting factor for germination and plant growth. To estimate the water requirements by the crops a soil water balance, was performed according to Pratt, Allen, Rosenberg, Keller, & Kopp (2019) (Equation (2)):

$$SWS_i = SWS_{i-1} + E_{pi} + I_i - ET_{ci} \quad (2)$$

Where:

SWS_i = soil water storage on day i (mm)

SWS_{i-1} = soil water storage on day $i-1$ (mm)

E_{pi} = effective precipitation on day i (mm)

I_i = irrigation on day i(mm)

ET_{ci} = crop evapotranspiration on day i (mm)

The soil water storage on day i (SWS_i, mm) gives the amount of water readily available to the crop on a daily basis (day i). SWS_{i-1} (mm) was determined using Equation (3) (Allen, Pereira, Raes, & Smith, 2006; Ministry of Agriculture, 2015):

$$SWS_{i-1} = \text{AWSC} * P_{soil} \quad (3)$$

Where:

AWSC = available water storage capacity in the soil (mm m^{-1}) (depends on soil texture, Table 1).

P_{soil} = soil rooting depth (m) (Table 1).

The effective precipitation was estimated using a fix percentage of the daily precipitation suggested by FAO (1992) (Equation (4)):

$$E_{pi} = aP_i \tag{4}$$

a = fix coefficient (0.8).

P_i = precipitation on day i (mm).

The total irrigation water supply to the crop for the whole season is given by (5):

$$I = \sum_i I_i \tag{5}$$

The climatological data was obtained from the Weather Stations Network at Universidad Nacional Autónoma de México (UNAM & PEMBU, 2022). For each orchard there was a weather station within a radius of 5 km (Table 1).

The reference evapotranspiration was calculated for each crop and urban garden, using the Penman- Monteith equation described in Allen *et al*. (2006) and implemented in Matlab v2018a with the following daily data: minimum and maximum temperature, minimum and maximum relative humidity, wind velocity and solar radiation from the years 2007-2018.

The crop evapotranspiration (mm d^{-1}) was obtained by multiplying the reference evapotranspiration by the crop coefficient, taking into account the different stages of the crop described in Figure 2.

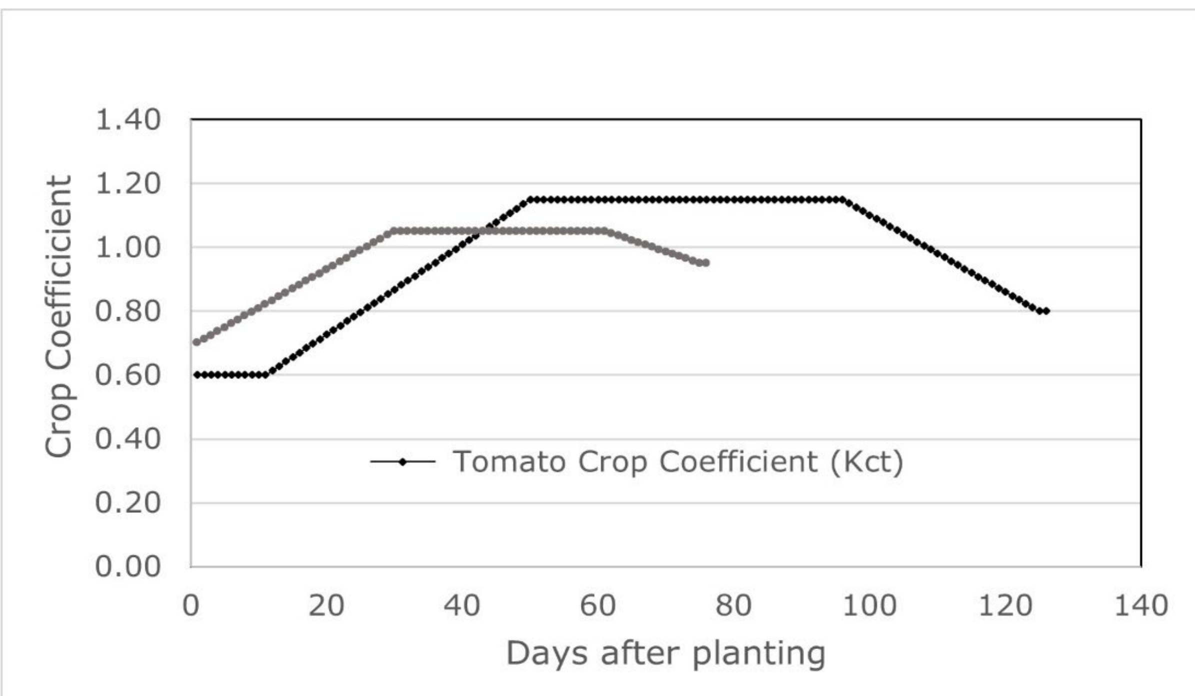

Figure 2. Crop coefficients of lettuce and cherry tomato. Own elaboration, values taken from Allen *et al*. (2006).

In all of the urban gardens, the irrigation to the crops is done in an empirical way. One of the purposes of this study was to demonstrate how much water can be saved if water is applied according to the requirements to the crop.

The daily irrigation I_i of lettuce and cherry tomato was obtained from the managers of each orchand who kept a daily record of the amount of water applied to the crop. In ten orchards water was applied using manual showers, and three orchards used drip irrigation system (Table 1).

The fraction of SWS that a crop can be extracted from the root zone without experiencing water stress is called water easily available or the daily maximum soil water deficit ($MSWD$, mm) (minimum amount of water in the soil to avoid crop stress) and it was calculated with Equation (6) (Angella & Salgado, 2016):

$$MSWDi = SWS_i * \rho \quad (6)$$

Where:

ρ = average fraction of total available soil water (SWS) that can be depleted from the root zone before stress occurs

For each urban garden, a record will be kept on the days after planting the crop is water stressed (PWS), which can have a direct effect on the crop yields.

The total crop water requirements $(WR_{ct}\ \mathrm{mm})$ in the season is presented in Equation (7). For the case of the urban gardens in greenhouses (C, F and G) P_i = 0 and then $E_{pt} = 0$:

$$WR_{ct} = ET_{ct} - E_{pt} \tag{7}$$

Where:

ET_{ct} =total crop evapotranspiration during the season (mm)

E_{pt} = total effective precipitation during the season (mm).

Because irrigation is done empirically, the difference between the total crop water requirements (WR_{ct}) (mm) and the total irrigation applied to the crops $(I)(mm)$ will estimate the deficit or excess of water applied to the crops.

Rainwater storage in the urban garden

The possible amount of rainwater collected in each orchard was estimated assuming a sheet roof, following the procedure described in FAO (2013) (Equation (8)):

$$Storage = \frac{P80\% * A * C}{1000} \tag{8}$$

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Where:

Storage = rainwater collected in m^3.

A = catchment area in m^2.

C = runoff coefficient (0.7).

$P80\ \%$ = exceedance probability at 80 % occurrence (mm).

The exceedance probability was obtained using Equation (9) suggested in FAO (2013):

$$P\% = \frac{m-0.375}{N+0.25} * 100 \qquad (9)$$

Where:

m = order number.

N = total number of observations.

Precipitation records (2007-2018) from 12 weather stations were used to calculate the 80 % exceedance probability (80 % of the years precipitation exceeds the value considered).

Results and discussion

Water balance in the soil

In all urban gardens, a daily water balance was performed for each crop using Equation (1). Table 2 presents a summary for a complete season of lettuce and cherry tomatoes. Since sowing till harvesting a daily comparison was made between the water available to the crops (SWS_i-SWS_{i-1}) and $MSWDi$ (Equation (6)). The number of days in which SWS_i-$SWS_{i-1} < MSWDi$ is displayed for each crop (Table 2) as the days after sowing the crop was water stressed (PWS). Only gardens A, I and J, registered many days in which plants were water stressed ($PWS>0$).

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Table 2. Soil water balance for the 13 urban gardens.

UG	Lettuce						Cherry Tomato					
	E_{pt}	ET_{ct}	WR_{ct}	I	I - WR_{ct}	PWS	E_{pt}	ET_{ct}	WR_{ct}	I	I - WR_{ct}	PWS
A	158	350	192	250	58	48, 56-75	374	522	148	380	232	60-74, 116-117
B	147	360	213	245	32	0	242	539	297	330	33	0
C	0	389	389	415	26	0	0	569	569	915	346	0
D	138	318	180	265	85	0	243	477	234	345	111	0
E	147	360	213	220	7	0	242	539	297	360	63	0
F	0	339	339	545	206	0	0	508	508	895	387	0
G	0	350	350	400	50	0	0	522	522	665	143	0
H	137	326	189	240	51	0	261	488	227	420	193	0
I	104	334	230	218	-12	44-93	278	504	226	322	96	48, 54-104,
												106-108, 112-126
J	114	382	268	330	62	44-73	217	569	352	538	186	46, 56, 58-72,
												110, 112-124
K	82	328	246	265	19	0	237	505	268	490	222	0
L	169	356	187	410	223	0	275	544	269	670	401	0
M	175	303	128	355	227	0	312	457	145	530	385	0

E_{pt} = Total effective precipitation during the season (mm)

ET_{ct} = Total crop evapotranspiration during the season (mm)

WR_{ct} =Total crop water requirements (mm)

I =Total irrigation water supply for the whole season (mm)

PWS =Days after planting the crop was water stressed.

Considering the entire production cycle, urban garden I presents an extreme case in which irrigation was below the water requirements of the lettuce crop ($I - WR_{ct} < 0$).

Although all urban gardens are located at the center and north of CDMX, there are important variations in the total effective precipitation (E_{pt}) and crop evapotranspiration (ET_{ct}) in the production cycle of lettuce and cherry tomato as described in Table 3, which have a great influence on the estimation of the water requirements of the crops.

Table 3. Total effective precipitation and evapotranspiration variations.

	Lettuce		**Cherry tomato**	
	E_{pt}	ET_{ct}	E_{pt}	ET_{ct}
Average	137.10	345.77	268.10	518.69
SD	29.35	24.53	45.84	33.60
Rank	93.00	86.00	157.00	112

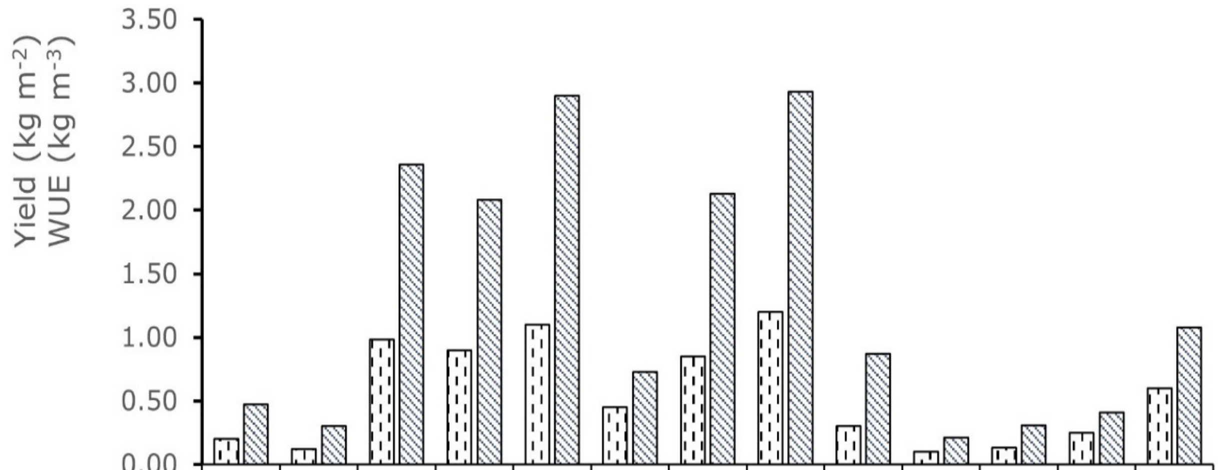
SD = Standard deviation

Crop yield and water use efficiency

The urban gardens show a big difference in yield and water use efficiency for both vegetables even though the same seedling and soil preparation compost and fertilizer NPK (14-10-34) was used.

Lettuce

Considering all urban gardens, lettuce yield varied between 0.10 and 1.20 kg m^{-2} and water use efficiency (WUE) ranged from 0.21 to 2.93 kg·m^{-3} (Figure 3). The highest yield and WUE were obtained for plants grown in the urban garden "H". However, these findings are below those reported by Sammis, Kratky, and Wu (1988) in an experiment with different water applications and transplanting dates. The authors harvested between 1.23 and 4.38 kg m^2 in terms of lettuce produced in Hawaii under open field conditions. Michelon *et al*. (2020) studied two lettuce cultivars with two EC treatments (1.2 and 1.8 dS m^{-1}) for a semiarid climate in Brazil and obtained similar lettuce yields above (1.8 kg m^{-2}) the ones found in the present study.



	A	B	C	D	E	F	G	H	I	J	K	L	M
Yield	0.20	0.12	0.98	0.90	1.10	0.45	0.85	1.20	0.30	0.10	0.13	0.25	0.60
WUE	0.47	0.30	2.36	2.08	2.90	0.73	2.13	2.93	0.87	0.21	0.31	0.41	1.08

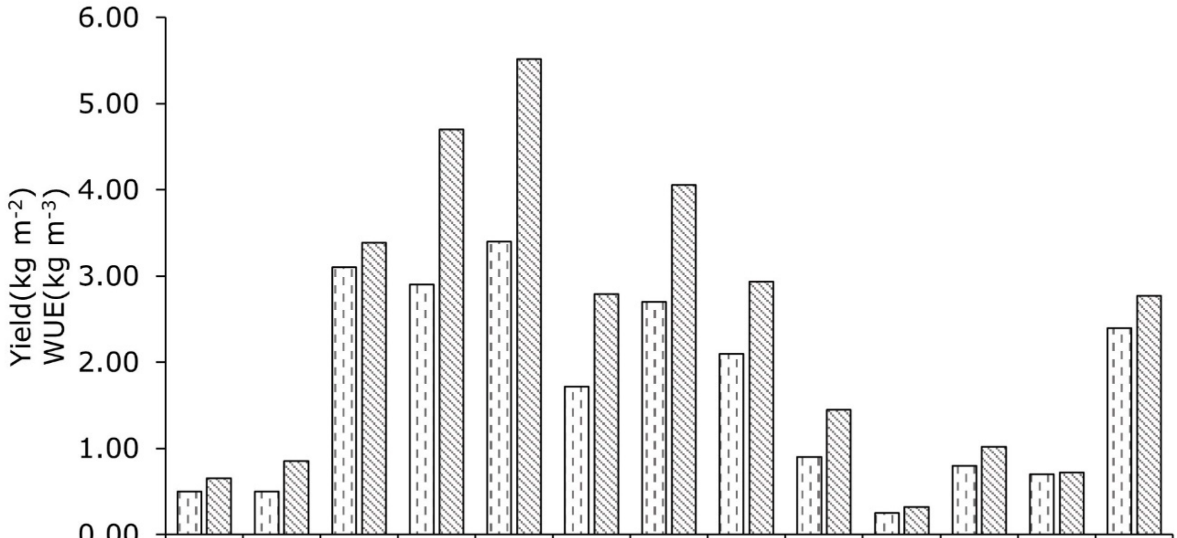
Figure 3. Yields and water use efficiency for lettuce in the urban gardens.

The WUE reported by Michelon *et al*. (2020) were between 8.54-38.4 kg m^{-3}. Also, Nederhoff and Stanghellini (2010) found a WUE of 7.5 kg m^{-3} for lettuce based on an average of 65 countries, these results are far above the ones in this study.

In contrast, Diansari (2019) calculated water use efficiencies ranging between 1.04 and 1.63 kg m^{-3} for lettuce plants grown under different peat compositions for an open field conditions in Indonesia, which are in the range of those obtained in our study.

Cherry tomato

The cherry tomato yields ranged between 0.25 and 3.4 kg m^{-2} (Figure 4). Yields less than 1 kg m^{-2} were measured in six urban gardens (A, B, I, J, K and L). It might be possible that different factors have influenced these results. Factors affecting yields could be: 1) soil texture which affects the water-holding capacity and consequently the crop yield (He & Wang, 2019); 2) soil depth which influences nutrient delivery and soil moisture (Murata *et al*., 2012); 3) water supply to the crop because plants with water stress can reduce yields (Sadras, Villalobos, Orgaz, Fereres, & Villalobos, 2016); 4) the salinity in the soil (Kumar, Wani, Suprasanna, & Tran, 2018).



	A	B	C	D	E	F	G	H	I	J	K	L	M
Yield	0.50	0.50	3.10	2.90	3.40	1.72	2.70	2.10	0.90	0.25	0.80	0.70	2.40
WUE	0.65	0.85	3.39	4.70	5.52	2.79	4.06	2.94	1.45	0.32	1.02	0.72	2.77

Urban garden

Figure 4. Yields and water use efficiency for cherry tomatoes in the urban gardens.

Orchards A, I, J, have a light soil texture (sandy coarse) and a bulk density of 2.65 g cm^{-3}. The AWSC is the same in the three gardens (60 mm). However, there are, 2 differences between them, soil depth (40, 30 and 20 cm) and the number of days at which the plants were water stressed (15, 67, 15). Even though garden A and J had the same number of days with water stress, the root depth in A is greater than J, resulting in higher yields of plants grown in A compared with J. Soil depth is very critical factor for plant growth and it can physically limit root penetration and create problems when using irrigation (Abd-Elmabod *et al*., 2019).

According to Lu *et al*. (2021), it might be possible that less roots were formed in the growth media with a low volume of soil, which is associated with a lower absorption of water and uptake of nutrients and therefore, a lower production of biomass. These findings agree with the fact that tomato plants produced in the urban garden E with a soil depth of 100 cm had the highest yield and water use efficiency, whereby roots can expand better and can absorb more nutrients.

Liu *et al*. (2019), for instance, asserts that water scarcity is the main constraint for high crop yields in many arid areas, particularly soil moisture level had a significant effect on tomato yield. However, no explanation was found for the low yields and WUE in gardens B and K, because crops were not water stressed and the soil depth was 100 and 80 cm, respectively. The fourth reason for a change in yield could be the salinity in the soil. Venkateswarlu (2012) asserts that salt concentration reduces osmotic potential of the soil solution creating water stress to root cells even under sufficient soil water availability. This assumption is confirmed by Huang *et al*. (2015), and Mohamed, El-Mogy, and Stevens (2018), who reported that cherry tomato yields decreased with increasing EC values in China and Egypt, respectivelly, so a further studies should be done in the soils of the urban gardens to know these parameters.

Considering all the urban gardens studied in CDMX, the water use efficiency for cherry tomato production was between 0.32 and 5.52 kg m^{-3} (Figure 4). These findings are far below the results as shown by van Veenhuizen (2006) (7.14 to 16.66 kg m^{-3}), and Nederhoff and Stanghellini (2010) (5.4 kg m^{-3}) for tomato crop.

We assume that some of our low values in terms of yield and WUE are due to water stress as shown for plants grown in the urban gardens A, I and J. However there are more factors that need to be studied in vegetables cultivated in the cities like contamination.

Future planning for the urban gardens

The studied urban gardens are located in the Center and North of CDMX. The rainy season is from June to September with a considerable variation in the amount of rainfall. Figure 5 gives an estimation of the rainwater per month using 80 % exceedance probability, which means that from a representative year within 2007-2018, the amount of rainfall per month varies from 0-138 mm. The possible rainwater storage exceedance probability (P80 %) depends on the rainfall and the available area dedicated to water storage in each urban garden.

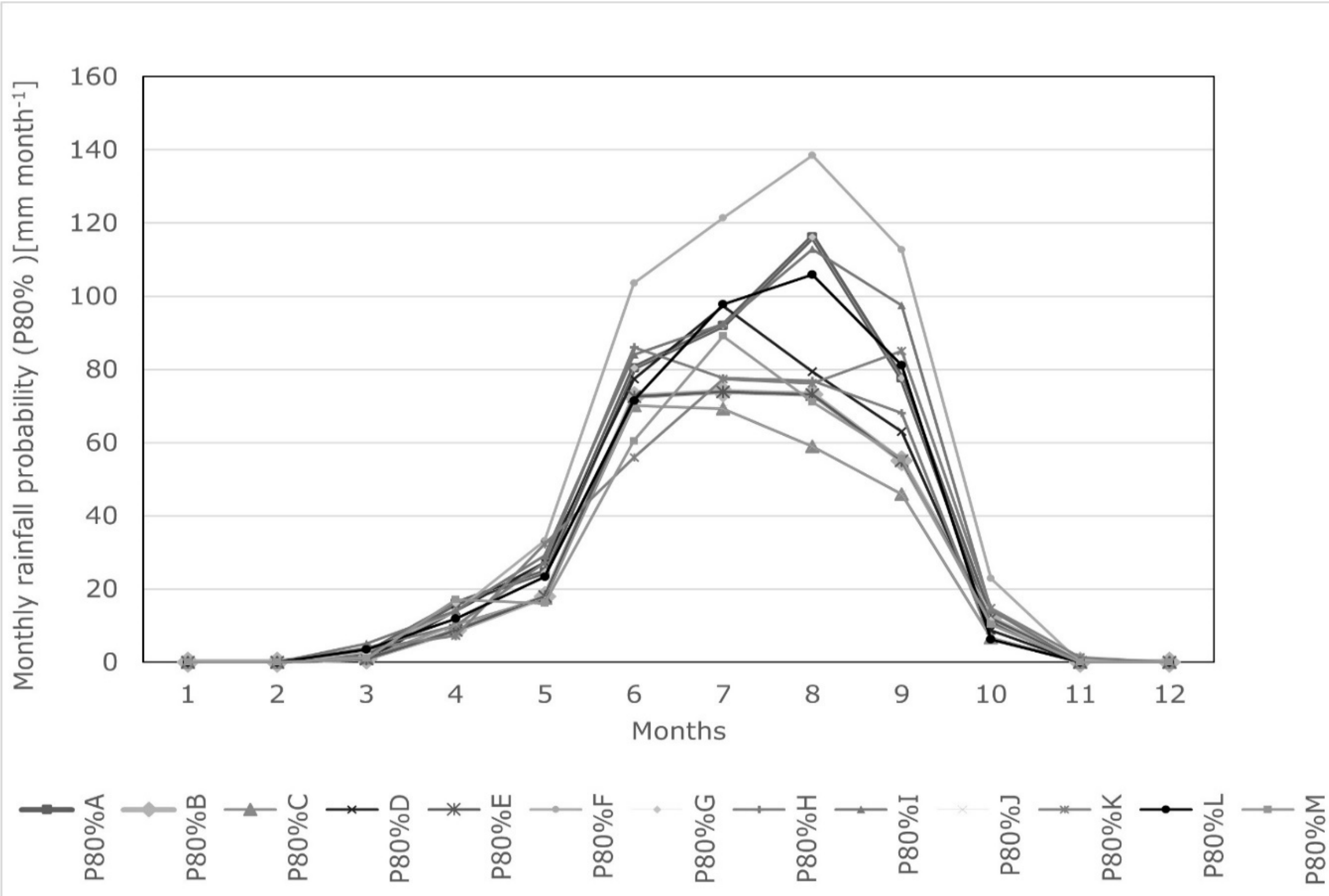


Figure 5. Estimation of the rainwater per month using an exceedance probability 80 % for the period 2007-2018.

The maximum P80 % recorded for the 13 urban gardens varies between 70 and 138 mm month^{-1}, which can generate an accumulated rainwater storage from 0.261 to 0.5215 m^{3} m^{-2} (Figure 6). So, it is recommended to storage the rainwater in the urban gardens, because it will be enough to meet most of the water requirements to grow lettuce

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(0.128-0.389 m^3 m^{-2}) or cherry tomato (0.145-0.569 m^3 m^{-2}) crops (Table 2).

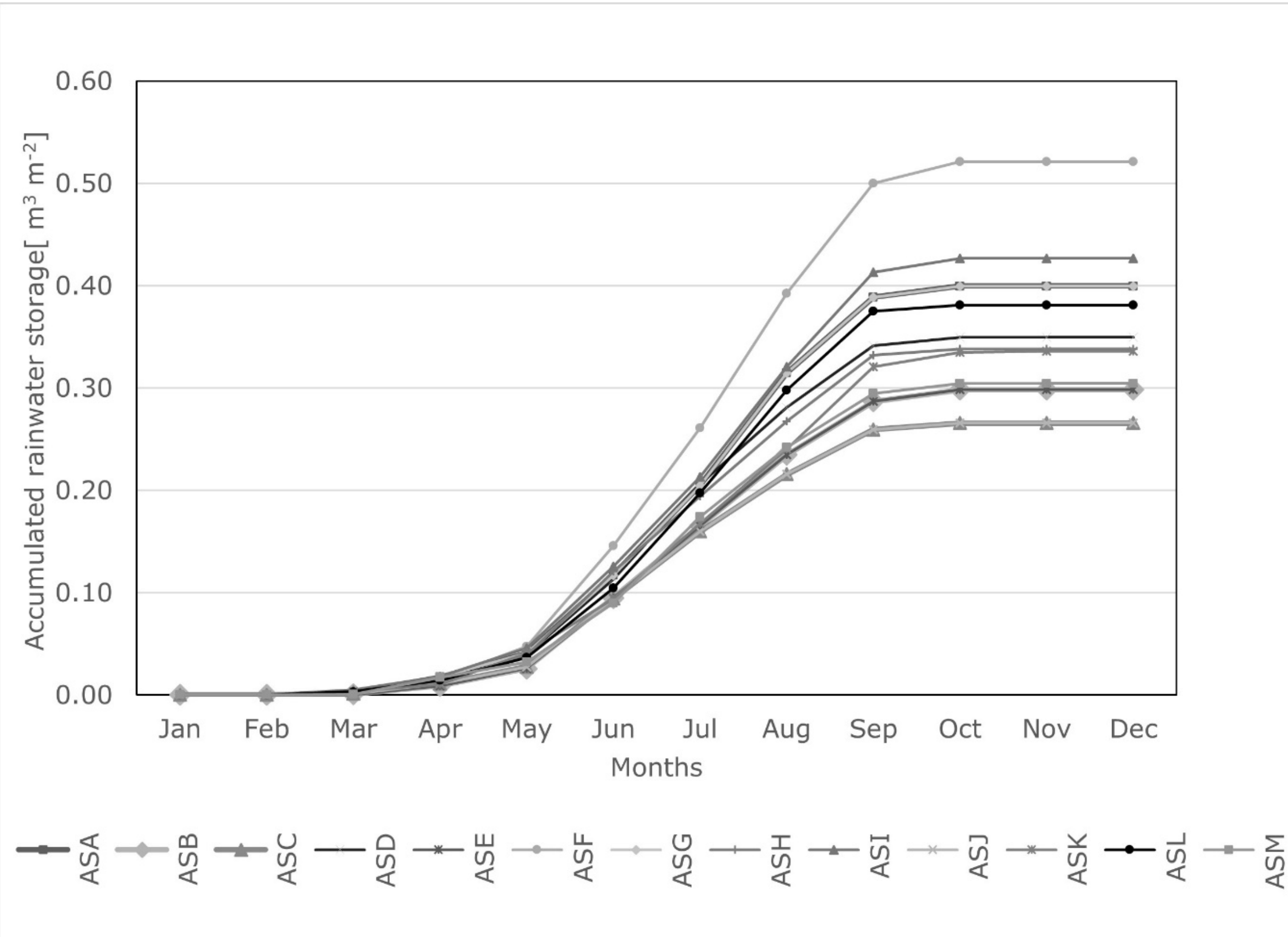

Figure 6. Accumulated rainwater storage (AS) for 13 urban gardens (A-M) for a representative year using rainwater estimation (P80 %).

Conclusions

In the present study, yields and water use efficiency of lettuce and cherry tomatoes, varied between different urban gardens in CDMX, which was mainly based on different growth conditions, such as soil conditions and water availability.

So far, the irrigation of vegetables in the urban gardens is done in an empirical way and it is mostly realized using fresh water. The water requirements to the crops were estimated based on effective precipitation and crop evapotranspiration calculated using data from the closest weather station from each urban garden. It was found that large water savings could be achieved if producers irrigate according to the water requirements of the crops. The maximum amount of water applied in excess for a growth season of lettuce and cherry tomato was 227 mm (0.227 m^3 m^{-2}) and 401 mm (0.401 m^3 m^{-2}), respectively which generates a low water use efficiency.

Rainwater harvesting is proposed as a solution to relieve the burden of fresh water use in urban agriculture. The stored rainwater (m^3 m^{-2}) may be enough to meet most of the crop water requirements to grow a complete season of lettuce or cherry tomato.

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References

Abd-Elmabod, S. K., Jordán, A., Fleskens, L., Phillips, J. D., Muñoz-Rojas, M., van-der-Ploeg, M., Anaya-Romero M., El-Ashry, S., & De-la-Rosa, D. (2017). Chapter 7. Modeling agricultural suitability along soil transects under current conditions and improved scenario of soil factorsb. In: Brevik, E., & Muñoz-Rojas, M. (eds.). *Soil mapping and process modeling for sustainable land use management* (pp. 193-219). Ámsterdam, The Netherlands: Elsevier Inc. DOI: 10.1016/B978-0-12-805200-6.00007-4

Allen, R. G., Pereira, L. S., Raes, D., & Smith, M. (2006). *Evapotranspiración del cultivo*. Roma, Italia: Organización de las Naciones Unidas para la Agricultura y la Alimentación. Recovered from http://www.fao.org/3/x0490s/x0490s.pdf

Amos, C. C., Rahman, A., Karim, F., & Gathenya, J. M. (2018). A scoping review of roof harvested rainwater usage in urban agriculture: Australia and Kenya in focus. *Journal of Cleaner Production*, 202, 174-190. DOI:10.1016/j.jclepro.2018.08.108

Angella, G. F., & Salgado, R. (2016). *Conceptos básicos de las relaciones agua-suelo-planta*. Recovered from https://www.researchgate.net/publication/322888562_Conceptos_basicos_de_las_relaciones_agua-suelo-planta/stats

Aubry, C., & Nastaran, M. (2019). Urban agriculture and health: Assessing risks and overseeing practices. *Field Actions Science Reports*, Special Issue 20(2019), Urban Agriculture: Another Way to Feed Cities. Recovered from http://journals.openedition.org/factsreports/5536

Bobadilla, S. E. E., Rivera H. G., & Del-Moral, B. L. E. (2010). Factores de competitividad del cultivo de lechuga en Santa María Jajalpa, Estado de México. *Análisis Económico*, 25(59), 143-154. Recovered from http://www.redalyc.org/articulo.oa?id=41315994009

Diansari, L. E. (2019). Water and land productivity of lettuce (*Lactuca sativa*) at floating on wetland. *Sriwijaya Journal of Environment*, 4(2), 104-108. DOI:10.22135/sje.2019.4.2.104-108

Garcia, M. R. (2018). El agua de lluvia de la CDMX, no apta para consumo humano directo. *Boletín UNAM-DGCS-670*. Recovered from https://www.dgcs.unam.mx/boletin/bdboletin/2018_670.html

FAO, Organización de las Naciones Unidas para la Alimentación y la Agricultura. (1992). Cropwat. Programa de ordenador para planificar y manejar el riego. FAO. *Estudios Riegos y Drenajes*, 46, 23-24. Recovered from https://www.mapa.gob.es/es/desarrollo-rural/temas/gestion-sostenible-regadios/precipitacionefectiva05_tcm30-82980.pdf

FAO, Organización de las Naciones Unidas para la Alimentación y la Agricultura. (2001). *Urban and periurban agriculture*. The special program for food security. Handbook Series Volume III. SPFS/DOC/27.8. Recovered from https://www.fao.org/unfao/bodies/coag/coag15/docs/X0076E

FAO, Organización de las Naciones Unidas para la Alimentación y la Agricultura. (2013). *Captación y almacenamiento de agua de lluvia*. Recovered from https://agua.org.mx/biblioteca/captacion-y-almacenamiento-de-agua-de-lluvia/

Farfan, J., Lohrmann, A., & Breyer, C. (2019). Integration of greenhouse agriculture to the energy infrastructure as an alimentary solution. *Renewable and Sustainable Energy Reviews*, 110, 368-377. DOI: 10.1016/j.rser.2019.04.084

He, D., & Wang, E. (2019). On the relation between soil water holding capacity and dryland crop productivity. *Geoderma*, 353, 11–24. DOI: 10.1016/j.geoderma.2019.06.022

Huang, C., Peng, F., You, Q., Xue, X., Wang, T., & Liao, J. (2015). Growth, yield and fruit quality of cherry tomato irrigated with saline water at different developmental stages. *Acta Agriculturae Scandinavica. Section B, Soil and Plant Science*, 66(4), 317-324. Recovered from https://scihub.tw/10.1080/09064710.2015.1111931

Khumalo, N., & Sibanda, M. (2019). Does Urban and Peri-Urban Agriculture Contribute to Household Food Security? An Assessment of the Food Security Status of Households in Tongaat, eThekwini Municipality. *Sustainability*, 11(4), 1082-1082. DOI: 10.3390/su11041082

Kumar, V., Wani, S. H., Suprasanna, P., & Tran, L. S. P. (eds.). (2018). *Salinity responses and tolerance in plants*. Vol. 2. Exploring RNAI, genome editing and systems biology. Berlin, Germany: Springer. DOI: 10.1007/978-3-319-90318-7

Li, W., Wang, D., Liu, S., y Zhu, Y. (2019). Measuring urbanization-occupation and internal conversion of peri-urban cultivated land to determine changes in the peri-urban agriculture of the black soil region. *Ecological Indicators*, 102, 328-337. DOI: 10.1016/j.ecolind.2019.02.055

Liu, J., Hu, T., Feng, P., Wang, L., Yang, S., & Aroca, R. (2019). Tomato yield and water use efficiency change with various soil moisture and potassium levels during different growth stages. *Plos One*, 14(3), 0213643. DOI: 10.1371/journal.pone.0213643

Lu, J., Shao, G., Gao, Y., Zhang, K., Wei, Q., & Cheng, J. (2021). Effects of water deficit combined with soil texture, soil bulk density and tomato variety on tomato fruit quality: A meta-analysis. *Agricultural Water Management*, 243. DOI: 10.1016/j.agwat.2020.106427

Lupia, F., & Pulighe, G. (2015). Water use and urban agriculture: Estimation and water saving scenarios for residential kitchen gardens. *Agriculture and Agricultural Science Procedia*, 4, 50-58. DOI: 10.1016/j.aaspro.2015.03.007

McDougall, R., Kristiansen, P., & Rader, R. (2019). Small-scale urban agriculture results in high yield but requires judicious management of inputs to achieve sustainability. *Proceedings of the National Academy of Sciences*, 116(1), 129-134. DOI: 10.1073/pnas.1809707115

McEldowney, J. (2017). L'agriculture urbaine en Europe. *Service the Recherche Por Les Députés. EPRS*. Recovered from https://www.europarl.europa.eu/RegData/etudes/IDAN/2017/614641/EPRS_IDA(2017) 614641_FR.pdf

Michelon, N., Pennisi, G., Myint, N. O., Dall'Olio, G., Batista, L. P., Salviano, A. A. C., Gruda, N. S., Orsini, F., & Gianquinto, G. (2020). Semi-arid climate. *Agronomy*, 10(1379). DOI: 10.3390/agronomy10091379

Ministry of Agriculture. (2015). Soil water storage capacity and available soil moisture. *Water Conservation. Factsheet* 619.000-1. Ministry of Agriculture British Columbia. Recovered from https://www.droughtmanagement.info/literature/BC_MA_Soil_Water_Storage_Capacity_2005.pdf

Mohamed, M., El-Mogy, C. G., & Stevens, R. (2018). Irrigation with salt water affects growth, yield, fruit quality, storability and marker-gene expression in cherry tomato. *Acta Agriculturae, Scandinavica, Section B. Soil & Plant Science*. DOI: 10.1080/09064710.2018.1473482

Murata, N., Ohta, S., Ishida, A., Kanzaki, M., Wachirinrat, C., Artchawakom, T., & Sase, H. (2012). Soil depth and soil water regime in a catchment where tropical dry evergreen and deciduous forests coexist. *Journal of Forest Research*, 17(1), 37-44. DOI: 10.1007/s10310-010-0248-z

Nederhoff, E., & Stanghellini, C. (2010). *Practical hydroponics & greenhouses*. Recovered from https://www.wur.nl/en/Publication-details.htm?publicationId=publication-way-333937333231

Pratt, T., Allen, L. N., Rosenberg, D. E., Keller, A. A., & Kopp, K. (2019). Urban agriculture and small farm water use: Case studies trends from Cache Valley, Utah. *Agricultural Water Management*, 213, 24-35. DOI: 10.1016/j.agwat.2018.09.034

Pulighe, G., & Lupia, F. (2019). Multitemporal geospatial evaluation of urban agriculture and (Non)-sustainable food self-provisioning in Milan, Italy. *Sustainability*, 11(7), 1846. DOI: 10.3390/su11071846

Sadras, V. O., Villalobos, F. J., Orgaz, F., Fereres, E., & Villalobos, F. J. (2016). Principles of agronomy for sustainable agriculture. In: *Effects of water stress on crop production* (pp. 189–204). Berlin, Germany: Springer International Publishing. DOI:10.1007/978-3-319-46116-8_14

Salazar, M. R., Rojano, A. A., & López , C. I. (2014). La eficiencia en el uso del agua en agricultura controlada. *Tecnología y ciencias del agua*, 5(2), 177-183. Recovered from http://www.revistatyca.org.mx/index.php/tyca/article/view/472/pdf

Sammis, T. W., Kratky, B. A., & Wu, I. P. (1988). Effects of limited irrigation on lettuce and chinese cabbage yield. *Irrigation Science*, (9), 187-198. DOI: 10.1007/BF00275431

SIAP, Servicio de Información Agroalimentaria y Pesquera. (2016). *Anuario estadístico de la producción agrícola*. Recovered from https://nube.siap.gob.mx/cierreagricola/

SIAP, Servicio de Información Agroalimentaria y Pesquera. (2019). *Anuario estadístico de la producción agrícola*. Recovered from https://nube.siap.gob.mx/cierreagricola/

Skara, S. L. G., Pineda, M. R., Timpec, A., Pölling, B., Bohne, K., Külvikf, M., Delgado, C., Pedras, C. M. G., Paço, T. A., Ćujić, M., Tzortzakis, N., Chrysargyris, A., Peticila, A., Alencikiene, G., Monsees, H., & Junge, R. (2020). Urban agriculture as a keystone contribution towards securing sustainable and healthy development for cities in the future. *Blue-Green Systems*, 2(1), 1–27. DOI: 10.2166/bgs.2019.931

Smith, M. (1992). CROPWAT, a computer program for irrigation planning and management. *FAO Irrigation and Drainage* (Paper 46). Rome, Italy: Food and Agriculture Organisation. Recovered from https://agris.fao.org/agris-search/search.do?recordID=SO2005100017

UNAM & PEMBU, Universidad Nacional Autónoma de México & Programa de Estaciones Meteorológicas del Bachillerato Universitario. (2022). *Red Universitaria de Observatorios Atmosféricos* (RUOA). Recovered from https://www.ruoa.unam.mx/pembu/

United Nations, Department of Economic and Social Affairs Population Division. (2019). *World Population Prospects 2019: Ten key findings*. Recovered from https://population.un.org/wpp

van Veenhuizen, R. (2006). Chapter 11. Urban horticulture. In: *Cities Farming for the Future, Urban Agriculture for Green and Productive Cities.* Recovered from https://www.idrc.ca/en/book/cities-farming-future-urban-agriculture-green-and-productive-cities

Venkateswarlu, B. (2012). *Crop stress and its management: Perspectives and strategies* (Ser. Life sciences). Recovered from https://epdf.pub/crop-stress-and-its-management-perspectives-and-strategies