Water and fertilizer efficiency in a polyculture cropping system under three production systems

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ABSTRACT

Approximately 40% of the water used in intensive agriculture is discarded as 'drainage,' which contains high amounts of ions that pollute the environment. This work aimed at investigating polyculture (tomatoes, cucumbers, and lettuce) under three production systems, namely, open (OPS), soil (SPS), and closed (CPS), in which the drainage water from the first crop was used to feed the second crop, and the water from the second crop was used to feed the third crop. The water and fertilizer efficiencies and some physical–chemical properties of the plants and soil were measured. The results showed no significant difference in the yield for polycultures between the CPS and OPS systems. The most efficient system for water use was the CPS, with 54.85 kg m^{-3}, with a water savings of 55.69% compared to the OPS. The efficiency of fertilizers, such as N, P, K, Ca, and Mg, was statistically higher in the CPS, providing more kilograms of fruit per kilogram of nutrients. The reuse of drainage water in a polyculture not only increased the efficiency of the water and fertilizers but also increased the yields produced per cubic meter of water used, thereby minimizing environmental contamination.

Key words | closed production system, drainage water reuse, fruit quality, intensive production

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INTRODUCTION

In 2009, the Food and Agriculture Organization of the United Nations (FAO) estimated that the global population in 2050 will be 9.3 billion; therefore, greater demands for water and food are expected. A 90% increase in food production due to increased yields from intensive production units is expected, whereas an increase of only 10% is expected due to the expansion of productive land (FAO 2009). However, the outlook for water use is not very encouraging, especially considering that the agricultural sector is responsible for 70% of the global freshwater withdrawal and more than 90% of the global consumption (FAO 2015). Therefore, the efficient use of this vital liquid is important. In intensive agriculture, to oxygenate the roots and wash excess salts from hydroponic substrates, the application of up to 40% extra nutrient solution to the plant is common (Schwarz *et al.* 2014). These solutions are commonly called 'drainage' and are mostly discharged to the ground, and they contain high amounts of ions, such as NO_3^-, PO_4^-, K^+, Ca^{2+}, and Mg^{2+}, which cause substantial contamination of the soil and aquifers.

To increase the efficiency of agricultural production and avoid contamination, it is necessary to not only use drainage containing high amounts of nutrients but also measure production in terms of the product produced per surface area (kg m^{-2}) relative to the product produced per quantity of water used (kg m^{-3}). Currently, tomatoes and cucumbers

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are the two crops with the highest demand (FAO 2019). Typically, these crops are cultivated in highly intensive production units, primarily as expansive monocultures in open production systems (OPSs) such as rock wool. These units generate high volumes of drainage that discharge principally to the ground. However, lettuce, which is commonly cultivated in soil production systems (SPSs), has high water consumption and requires predominantly nitrogen fertilizers, although it is one of the best-adapted crops to closed production systems (CPSs). The use of recycled drainage water in crop production, primarily in systems such as CPSs, has been shown to improve the uptake efficiencies of water and fertilizer in crops such as tomatoes (Katsoulas *et al.* 2015), cucumbers (Grewal *et al.* 2011), and lettuce (Moreno-Pérez *et al.* 2015). In addition to saving water, CPSs also conserve fertilizers; for example, good N efficiencies have been reported in tomatoes, cucumbers, and lettuce (Grewal *et al.* 2011; Thompson *et al.* 2013; Moreno-Pérez *et al.* 2015), and slightly less efficiencies have been found for P and K in these crops (Gent & Short 2012; Moreno-Pérez *et al.* 2015).

A primary reason for not reusing drainage water on the same crop it derives from is that it contains minerals, primarily Na, that can generate imbalances in plant nutrition, causing abnormalities or toxicity in the plant. Imbalances occur when the nutrient solution contains high concentrations of sodium chloride (NaCl), bicarbonates (HCO_3^-), calcium (Ca^{2+}), or magnesium (Mg^{2+}) (Dasgan & Ekici 2005). Therefore, the electrical conductivity (EC) and Na concentration in the drainage solution are used as indicators to determine if the residue of the nutrient solution, i.e., the 'drainage,' is still suitable for the plant (Katsoulas *et al.* 2015). Inadequate monitoring has the potential to cause imbalances in the supply of nutrients and thereby lead to excessive vegetative growth, uneven plant development and/or fruit maturation, or qualitative/quantitative reductions in yield (Pedrero *et al.* 2010).

Several investigations have focused on determining the water use efficiency (WUE) and nutrient use efficiency (NUE) in crops, focusing primarily on reusing drainage water in the same crop. However, producers have reservations regarding the reuse of drainage water in irrigation systems because of the potential plant health problems and other concerns. Little practical information exists to help producers decide whether they can reuse drainage water in different crops representing different families of plants without placing the primary crop at risk. Studies of the use of drainage with different types of plants of commercial interest are needed wherein diseases potentially dispersed by the drainage of one crop are not compatible with the next crop and thus cannot compromise the following crop's production. In previous research by Katsoulas *et al.* (2015) in tomato, by Grewal *et al.* (2011) in cucumber, and by Moreno-Pérez *et al.* (2015) in lettuce, only the efficiencies of water and fertilizer use in a single crop are reported. In contrast, in the present work, the polyculture of these crops is conducted wherein the drainage water of the first crop (tomato) is used to feed the second crop (cucumber), and the drainage water of the second is used to feed the third crop (lettuce). In this approach, the use of the initial water and the reused water in the second and third crops and the nutrients they contain are maximized. The objective of this study was to determine the WUE and NUE and several physiological variables in a polyculture (tomatoes, cucumbers, and lettuce) under three greenhouse production systems: a CPS, an OPS, and an SPS.

MATERIALS AND METHODS

Field characteristics and agronomic conditions

This research was performed in a greenhouse using the indeterminate tomato (*Solanum lycopersicum* L.) cultivar 'El Cid' (Harris Moran, Mexico), the indeterminate cucumber (*Cucumis sativus* L.) cultivar 'Kenya' (De Ruiter Seeds, Mexico), and the lettuce (*Lactuca sativa* L.) cultivar 'Sangria' (Shamrock, USA) in 2017 (January to August). The experiment was conducted at the Universidad Autónoma de Querétaro (20°11′N, 100°08′W, altitude 2,200 masl) in Mexico. The plants were grown in a naturally ventilated greenhouse in three plots measuring 10×20 m each.

The climatic conditions were measured using a weather station inside the greenhouse and recorded with a data logger (WatchDog, Spectrum Technologies Inc., USA). The maximum and minimum average temperatures during the investigation were 21.72 and 9.15 °C, respectively; the average relative humidity levels of day and night were 59.9% and 79.6%, respectively; and the average solar radiation was 893 W m^{-2}.

The soil used for the plants in the SPS had a field capacity (FC) of 28.8%, a wilting point of 17.14 (dew), a hydraulic conductivity (HC) of 4.1 cm hr^{-1}, and a bulk density (BD) of 1 g cm^{-3}. The primary characteristics of the soil layer (0–60 cm) were as follows: sand, 43.2%; loam, 28.3%; clay, 28.5%; organic matter, 1.24%; EC, 0.06 dS m^{-1}; and pH, 6.66. The chemical properties were (in mg kg^{-1}) mineral NO_3–N, 3.46; P-Bray, 0.61; Ac-extractable K_2O, 173; Ca, 1,557; Mg, 340; and Na, 14.95. The plants that were grown hydroponically were grown in rockwool slabs (Grodan, USA) measuring 1 × 0.20 × 0.075 m except for the hydroponic lettuce, which was cultivated in containers measuring 1 × 1 × 0.15 m using the floating root technique.

To allow the reuse of drainage between crops, the crops were planted in intervals. Tomatoes were planted first (27 January 2017). Twelve days after tomato emergence, cucumbers were planted; then, 16 days after cucumber emergence, lettuce was planted. A second planting of lettuce was conducted 105 days after the first planting. Transplanting was performed when the tomatoes presented three true leaves, and 26 days later, cucumber transplanting was performed; in both cases, plantlets were transplanted at a density of 2.5 plants m^{-2}. The lettuce was transplanted when the plants presented four true leaves, at 27 days after the cucumber transplanting, with a density of 18 plants m^{-2} in the CPS (floating root method). For the production system in soil, the plant density was 3.5 plants m^{-2}.

Drip irrigation was used for all the production systems except the lettuce in the CPS, in which the floating root technique was used, replenishing only the water consumed by the plant. The amount of water applied to the tomatoes and cucumbers in the OPS and CPS was controlled through drainage management and ranged from 25 to 30% (according to Schwarz *et al.* (2014)), whereas for the SPS, water application was performed by means of an automatic tensiometer (Irrometer, USA) at 18 centibars placed at 0.2 m depth for tomatoes and cucumbers. In all crops, the amount of water used for irrigation varied according to the phenological stage.

During the experiment, standard agronomic management practices for cucumbers, tomatoes, and lettuce were used. For the SPS, the soil was subsoiled to 45 cm deep before transplanting. For the OPS and SPS, the nutrient solution for the tomato and cucumber crops had a conductivity of 1.5 dS m^{-1} from the transplant to the third floral cluster, 2 dS m^{-1} from the third to the sixth floral cluster, and 2.5 dS m^{-1} from the sixth floral cluster until the end of the experiment (Ávila-Juárez *et al.* 2015). The nutrient solution used was Steiner (1984) solution, which consists of (in mg L^{-1}) N, 167; P, 31; K, 277; Mg, 49; Ca, 183; S, 111; Fe, 1.33; Mn, 0.62; B, 0.44; Cu, 0.02; Zn, 0.11; and Mo, 0.048, prepared at a pH of 5.8. The same nutrient solution conditions were used for the CPS, and the tomato drainage was readjusted according to Ávila-Juárez *et al.* (2015) to feed the cucumber crop. To feed the lettuce, the drainage from the cucumber crop was used. Pest and disease control was performed in accordance with local management practices.

The fruits of the tomatoes, cucumbers, and lettuce were harvested when they presented commercial harvest characteristics at maturity. For the tomatoes, 12 clusters were harvested; for the cucumbers, 10 cuts were made; and for the lettuce, two harvests were made (two production cycles).

Treatments and experimental design

Three types of production systems were used (treatments). The OPS involved the polyculture of tomatoes, cucumbers, and lettuce grown in rockwool slabs (Grodan, USA), for which the drainage from the plants was not used. The soil production system (SPS) consisted of a polyculture of tomatoes, cucumbers, and lettuce grown in soil, and the drainage was not collected from any crop. In the CPS, the tomatoes and cucumbers were cultivated in rockwool slabs (Grodan, USA), whereas the lettuce was grown in containers according to the floating root technique. In the CPS, the drainage of the tomato crop was collected, disinfected, measured, subjected to chemical analysis, and readjusted for nutrients, such as N, P, K, Ca, and Mg, for use in the cucumber crop. To feed the lettuce crop, the cucumber crop drainage was collected, measured, disinfected, subjected to nutrient analysis, and readjusted for nutrients, such as N, P, K, Ca, and Mg. A lamp that emitted 30 W of UV light was used to disinfect the drainage (Evans, USA).

The experiment was conducted in a randomized complete block design with three treatments (types of production systems) and eight replicates.

Water, soil, plant, and fruit analyses

Water chemical analysis

The drainage water of plants to be used to feed another crop in the same treatment was collected in dark containers and analyzed immediately in triplicate. The following parameters were measured: pH; EC (EC_D; dS m^{-1}); nutrient contents (in mg L^{-1}) of nitrate-N (NO_3-N), phosphorus (PO_4-P), potassium (K^+), calcium (Ca^{2+}), and magnesium (Mg^{2+}); sodium (Na^+, ppm); and dissolved oxygen (O_2, ppm).

The pH and EC_D were measured using a combination of waterproof pH and EC meter (Hanna Inc., USA). The Na^+ was measured with an ion-selective meter (Horiba, USA), whereas the O_2 was measured with a model HI83209 photometer (Hanna Inc., USA). The analysis of nutrients (NO_3-N, PO_4-P, K^+, Ca^{2+}, and Mg^{2+}) was performed using a model HI83225 photometer (Hanna Inc., USA).

Soil chemical and physical analyses

The following physical properties were determined: saturation (SAT; %), FC (%), wilting point (WP; %), HC (cm hr^{-1}), BD (g cm^{-3}), cation exchange capacity (CEC, meq 100 g^{-1}), and ECs (dS m^{-1}). The chemical properties determined included organic matter (OM; %), pH, and the nutrients (mg kg^{-1}) inorganic nitrogen (NO_3-N) and total P, K, Ca, Mg, and Na.

NO_3-N content was determined according to the Kjeldahl method, whereas the pH and the EC were determined with a potentiometer (Conductronic, Mexico) according to Mexican standard NMX-FF-109-SCFI-2007. The K, Ca, Mg, and Na contents were analyzed by atomic absorption after wet digestion of the material. P was determined after digestion and calcination.

Plant and fruit analyses

For each crop, the measured physiological variables were stem diameter (SD); plant height; leaf chlorophyll level, which was reported in SPAD units (every 15 days, as measured on the fourth developed young leaf) using a chlorophyll meter (SPAD 502, USA); and total yield (t ha^{-1}). Using a sample of 10 fruits per treatment, the following parameters were measured: equatorial diameter (cm); fruit length (cm); fresh fruit weight (g); content of soluble solids (°Brix), measured with a refractometer (Hanna Inc., USA); and fruit firmness (kgf), measured with a penetrometer fruit pressure tester (QA Supplies, USA).

Water and fertilizer efficiency

Water use efficiency and total net water

The WUE (kg m^{-3}) was calculated as

$$\mathrm{WUE} = \frac{Y}{I} \tag{1}$$

where Y is the yield (kg ha^{-1}), and I is the amount of water used in the crop (m^3).

The total net water (NWT; m^3 ha^{-1}) was calculated as

$$\mathrm{NWT} = W_I - W_d \tag{2}$$

where W_I is the net water applied to the plant (m^3), and W_d is the reused drainage water (m^3).

Fertilizer use efficiency

The use efficiency of fertilizer (NUE, kilogram of fruit per kilogram of nutrient) was calculated as

$$\mathrm{NUE} = \frac{Y}{F} \tag{3}$$

where Y is the total yield (kg), and F is the nutrient used (N, P, K, Ca, and Mg) in kg.

Statistical analysis

Analysis of variance (ANOVA) was performed using OriginPro 8.0 software (USA). Where differences were found among treatments, pairwise comparisons were performed using Tukey's method at the 0.05 probability level.

RESULTS AND DISCUSSION

Yield and fruit variables

The highest yields of the production systems were obtained for tomatoes, at 143.41 t ha^{-1}, in the SPS and cucumbers. at 130.81 t ha^{-1}, in the CPS. For lettuce, production did not significantly differ between the OPS and CPS, with yields of 68.40 and 62.79 t ha^{-1}, respectively (Figure 1). However, the total yield of the polyculture (the average sum of tomato, cucumber, and lettuce yield) significantly differed between CPS and OPS (Figure 1). These results showed that the drainage water from some crops used to feed other crops following readjustment for nutrients was of good quality and improved yields relative to those under the OPS, in which the drainage was discarded. Tomato fruit weight was higher in the SPS system than in the other systems, possibly because the fruit required a longer time to mature in this system than in the other systems; this longer time was due to the low temperature in the root zone (data not shown), which delayed ripening in this system relative to that in the other systems of production. The number of fruits did not significantly differ between the SPS and CPS systems, but the number was significantly higher in both of these systems than in the OPS (Table 1).

Table 2 shows that the tomatoes achieved greater plant height and SD in the SPS than in the other systems. For the lettuce, a greater fruit diameter was obtained in the

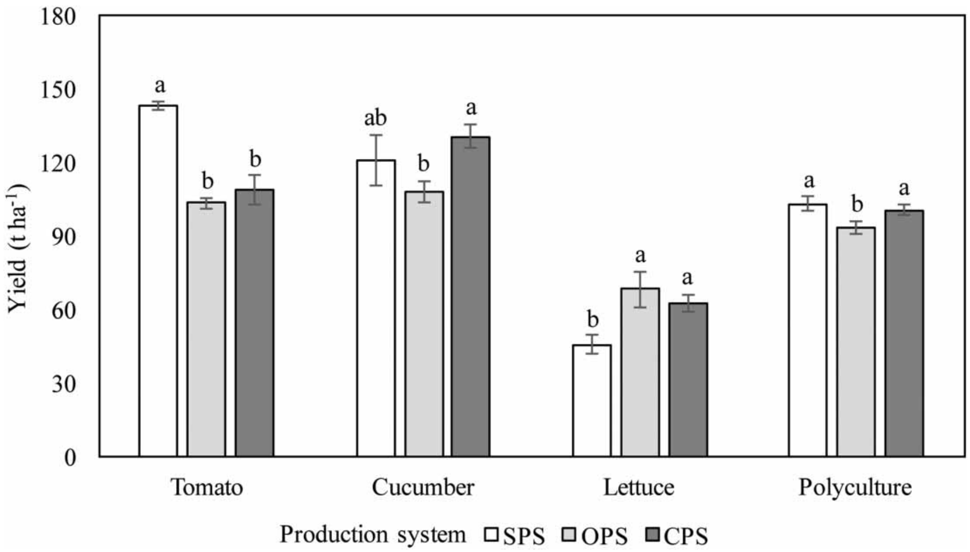

Figure 1 | Average yields (means ± standard error) of tomato, cucumber and lettuce plants ($n = 12$) grown under three production systems. Different letters above bars indicate significant differences ($p < 0.05$) among systems in yield within a crop ('Tomato', 'Cucumber', 'Lettuce') or in average sum yield of the three crops ('Polyculture').

Table 1 | Fruit variables in a polyculture of tomatoes, cucumbers, and lettuce under three production systems: soil (SPS), open (OPS), and closed (CPS)

Production system	Fruit number plant^{-1}		Single fruit weight (g)			Equatorial diameter (cm)		Polar diameter (cm)	Fruit length (cm)
	Tomato	Cucumber	Tomato	Cucumber	Lettuce	Tomato	Cucumber	Tomato	Cucumber
SPS	38.25 ± 0.29 a	12.00 ± 1.08 a	136.32 ± 12.62 a	389.91 ± 18.56 a	652.18 ± 53.67 a	56.11 ± 5.00 a	56.68 ± 2.69 a	67.34 ± 5.89 a	21.72 ± 1.27 a
OPS	34.00 ± 1.08 b	12.25 ± 0.65 a	118.05 ± 6.22 b	361.22 ± 21.46 a	402.36 ± 43.85 b	70.33 ± 30.53 a	53.89 ± 0.97 a	69.44 ± 0.93 a	21.53 ± 0.80 a
CPS	38.00 ± 0.01 a	12.88 ± 1.31 a	112.29 ± 7.61 b	369.52 ± 37.09 a	369.34 ± 21.92 b	53.93 ± 1.49 a	50.52 ± 3.36 a	67.37 ± 2.54 a	21.17 ± 1.46 a

The data represent the mean ± standard error ($n = 12$). Different letters within a column indicate significant differences ($p < 0.05$).

Table 2 | Physiological variables and SPAD units in a polyculture of tomatoes, cucumbers, and lettuce under three production systems: soil (SPS), open (OPS), and closed (CPS)

Production system	Plant height (cm)			Stem diameter (mm)			SPAD units		
	Tomato	Cucumber	Lettuce	Tomato	Cucumber	Lettuce	Tomato	Cucumber	Lettuce
SPS	451.18 ± 18.33 a	279.89 ± 25.45 a	18.84 ± 0.97 b	7.95 ± 0.61 a	5.02 ± 0.14 a	27.81 ± 1.86 a	53.62 ± 1.30 a	48.67 ± 0.85 a	35.96 ± 1.60 a
OPS	424.31 ± 8.08 b	270.13 ± 19.39 a	22.04 ± 0.69 a	6.07 ± 0.23 b	4.98 ± 0.31 a	23.56 ± 2.18 b	54.75 ± 0.84 a	47.12 ± 0.40 a	33.58 ± 1.80 a
CPS	421.28 ± 10.46 b	280.94 ± 24.01 a	20.62 ± 0.67 a	6.18 ± 0.32 b	4.84 ± 0.18 a	22.50 ± 1.10 b	54.48 ± 1.04 a	46.80 ± 1.72 a	34.53 ± 1.09 a

The data represent the mean ± standard error ($n = 12$). Different letters within a column indicate significant differences ($p < 0.05$).

SPS than in the other systems. However, although the average weight per fruit was higher in the SPS than in the other systems, the total yield (kg ha^{-1}) was lower in the SPS since the soil plant density per square meter, 18 plants m^{-2}, was lower in this system than in the other systems. SPAD units are directly related to the concentration of chlorophyll in the leaf, and the leaf chlorophyll content is directly related to the photosynthetic capacity of the crop (Jiang *et al.* 2017). We did not find significant differences in the SPAD units of any crop among the different production systems (Table 2), so we can infer that CPSs can achieve similar results as OPSs while being more environmentally friendly, as the WUE of a CPS is enhanced through reuse in other crops. Regarding fruit quality of tomato and cucumber fruits, Table 3 shows that no significant differences in °Brix and firmness were found between the conventional production system (OPS) and the CPS.

Table 3 | Brix and firmness in tomato and cucumber fruit grown under three production systems: soil (SPS), open (OPS), and closed (CPS)

Production system	°Brix		Firmness (kgf)	
	Tomato	Cucumber	Tomato	Cucumber
SPS	4.78 ± 0.42 b	3.72 ± 0.17 a	3.87 ± 0.25 b	8.16 ± 0.49 a
OPS	6.04 ± 0.26 a	3.68 ± 0.05 a	4.35 ± 0.24 a	7.65 ± 0.36 a
CPS	5.59 ± 0.16 a	3.42 ± 0.51 a	4.39 ± 0.19 a	7.67 ± 0.74 a

The data represent the mean ± standard error ($n = 10$). Different letters within a column indicate significant differences ($p < 0.05$).

Water and fertilizer efficiency

For cucumbers and lettuce, the highest WUE values among the systems were obtained in the CPS. In addition, regarding the average total WUE of the three crops (polyculture), the CPS yielded an average of 55.69% water savings relative to the OPS and a 34.70% savings relative to the SPS (Table 4). Furthermore, the NWT applied to the polyculture was greater under the OPS than in the other systems in this investigation, which was expected since the OPS does not benefit from the drainage and the SPS underuses the water because much of the solution (up to 50%) infiltrates the subsoil. Thus, the best results were obtained with the CPS, with a net water application that was 23.46% and 21.01% lower than that in the OPS and SPS, respectively (Table 4). These results are very important because water scarcity

Table 4 | Water use efficiency (WUE) and total net water (NWT) in three crops, tomatoes, cucumbers, and lettuce, under three production systems: soil (SPS), open (OPS), and closed (CPS)

Production system	WUE (kg m^{-3})				NWT (m^3 ha^{-1})			
	Tomato	Cucumber	Lettuce	Polyculture	Tomato	Cucumber	Lettuce	Polyculture
SPS	27.10 ± 0.30 a	62.98 ± 5.48 b	32.08 ± 2.64 b	40.72 ± 1.24 b	5,292.00	1,922.10	1,423.28	2,879.13
OPS	21.81 ± 0.49 b	48.11 ± 1.96 c	35.77 ± 3.90 b	35.23 ± 1.14 c	4,742.63	2,260.25	1,912.5	2,971.79
CPS	26.74 ± 1.45 a	88.82 ± 3.18 a	49.00 ± 2.91 a	54.85 ± 1.16 a	4,067.78	1,472.83	1,281.53	2,274.05

The data represent the mean ± standard error ($n = 8$). Different letters within a column indicate significant differences ($p < 0.05$). The polyculture is the mean ± standard error of the tomato, cucumber, and lettuce variables within a production system.

has become a major concern, posing serious threats to both food security and the economy in many parts of the world (Alam 2015). However, for producers to adopt water-saving technologies, understandable technical information is needed (Negatu & Parikh 1999). The nutrient measurement equipment for drainage used in the present study is economically accessible to producers; thus polyculture can easily be adapted for use in any production area.

However, an NUE of 141.34 kg of tomatoes was obtained for each kilogram of N used in the CPS; this value was higher than that in the OPS but not that in the SPS. In contrast, the highest NUE in cucumbers and lettuce was obtained in the CPS. The NUE for nitrogen in the cucumber crop was 75.73% higher in the CPS than in the OPS and 27.72% higher in the CPS than in the SPS. In lettuce, in the CPS, the NUE of N was 17.85% higher than that in the OPS and 51.31% higher than that in the SPS. Furthermore, for polyculture, the CPS yielded the highest NUE of N, with an average 40.89% higher than that in the OPS and 26% higher than that in the SPS (Table 5). The primary reason for the lower NUE in the SPS is that 50–70% of the total N applied to the soil is lost via runoff, denitrification, volatilization, and leaching (Montemurro & Diacono 2016). Various techniques to improve the efficiency of N have been developed, such as for grafts in tomato plants (Djidonou *et al.* 2013). However, it is problematic to use drainage in an OPS because drainage is known to contain several macroelements that are potentially harmful, and this practice risks the agricultural sustainability of the system and the health of the environment (Yasuor *et al.* 2013). At the polyculture level, the NUE of P in the CPS was 9% higher than that in the SPS and 21.87% higher than that in the OPS. For K, the greatest NUE was obtained with the CPS, being 22.92% higher in this system than in the SPS and 37.22% higher in this system than in the OPS. Calcium was the element with the highest use efficiency, with an NUE higher in the CPS than in the SPS (216%) and the OPS (249%). Similar results were obtained for magnesium, with the CPS yielded the highest NUE among the systems (Table 5).

Physical and chemical properties of the soil

Table 6 shows that the improper use of fertilizers can affect the physical–chemical structure of the soil, leaving large

Table 5 | Nutrient use efficiency (NUE) in three crops, tomatoes, cucumbers, and lettuce, under three soil production systems: soil (SPS), open (OPS), and closed (CPS)

	Tomato (kg fruit kg nutrient^{-1})			**Cucumber (kg fruit kg nutrient^{-1})**			**Lettuce (kg fruit kg nutrient^{-1})**			**Polyculture (kg fruit kg nutrient^{-1})**		
Nutrient	**SPS**	**OPS**	**CPS**	**SPS**	**OPS**	**CPS**	**SPS**	**OPS**	**CPS**	**SPS**	**OPS**	**CPS**
N	175.4 ± 1.9 a	120.86 ± 2.7 c	141.34 ± 7.7 b	446.11 ± 38.8 b	324.24 ± 13.2 c	569.80 ± 20.4 a	284.02 ± 23.4 c	364.65 ± 39.7 b	429.77 ± 25.5 a	301.84 ± 8.2 b	269.92 ± 11.5 c	380.31 ± 8.9 a
P	944.92 ± 10.34 a	651.10 ± 14.5 c	795.80 ± 43.2 b	2,403.24 ± 209.0 a	1,746.69 ± 71.3 b	2,258.63 ± 80.8 a	1,530.04 ± 125.9 b	1,964.42 ± 214.1 a	2,261.95 ± 134.2 a	1,626.07 ± 44.4 b	1,454.04 ± 62.1 c	1,772.13 ± 47.8 a
K	105.75 ± 1.2 a	73.75 ± 3.3 c	85.64 ± 4.6 b	268.95 ± 23.4 b	195.48 ± 8.0 c	321.99 ± 11.5 a	171.23 ± 14.1 c	219.85 ± 24.0 b	263.47 ± 15.6 a	181.98 ± 5.0 b	163.02 ± 6.9 c	223.70 ± 5.4 a
Ca	160.07 ± 1.7 a	118.73 ± 17.0 b	151.46 ± 8.2 a	407.11 ± 35.4 b	295.89 ± 12.1 c	1,662.83 ± 59.5 a	259.19 ± 21.3 c	332.77 ± 36.3 b	797.56 ± 47.3 a	275.45 ± 7.5 b	249.13 ± 16.0 b	870.62 ± 17.8 a
Mg	597.81 ± 6.5 a	411.92 ± 9.2 c	547.86 ± 29.7 b	1,520.42 ± 132.3 b	1,105.05 ± 45.1 c	4,468.40 ± 160.0 a	967.99 ± 79.6 b	1,242.80 ± 135.4 b	3,146.70 ± 186.8 a	1,028.74 ± 28.1 b	919.92 ± 39.3 c	2,720.99 ± 60.4 a

The data represent the mean ± standard error ($n = 8$). Different letters within a row and crop indicate significant differences ($p < 0.05$). The 'Polyculture' columns present the mean ± standard error of the tomato, cucumber, and lettuce variables for a given production system.

Table 6 | Soil properties (30 cm depth) before and after the experiment with a polyculture

		Soil after		
	Soil before	Tomato	Cucumber	Lettuce
Physical properties				
SAT (%)	53.95	67.60	61.60	63.60
FC (%)	28.85	36.30	33	34.10
WP (%)	17.15	21.60	19.60	20.30
HC (cm hr^{-1})	4.10	0.60	0.90	0.90
BD (g cm^{-3})	1	0.92	0.90	0.92
ECs (dS m^{-1})	0.06	3.68	3.38	2.32
CEC (meq 100 g^{-1})	11.05	20.60	21.20	15.80
Chemical properties				
OM (%)	1.12	2.79	2.80	2.75
pH (1:2 water)	6.66	6.81	6.77	6.88
NO_3-N (mg kg^{-1})	3.46	163	107	46.70
P-Bray (mg kg^{-1})	0.61	41.70	55.90	52.50
K (mg kg^{-1})	173	880	714	543
Ca (mg kg^{-1})	1,557	2,946	3,090	2,296
Mg (mg kg^{-1})	340	408	438	321
Na (mg kg^{-1})	14.95	70.30	85.60	63.20

amounts of unused nutrients in the soil. For example, soil EC was several times higher once the crop was finished than it was at the beginning of the experiment. A high EC can cause not only alterations to the subsequent crops but also contamination of aquifers. A 6.8-fold reduction was observed in HC in the tomato crop, whereas for the cucumbers and lettuce, 4.5-fold reductions were observed. Such changes can lead to problems in subsequent cycles, including not only a reduction in yield if the HC falls below 0.5 cm hr^{-1} (Saunders *et al.* 1978) but also a reduction in the infiltration of water into the soil, causing increases in ions such as sodium ions (Ávila-Juárez *et al.* 2015). Soil salinization causes reductions in the cultivated area and in the quality and productivity of crops (Yamaguchi & Blumwald 2005; Shahbaz & Ashraf 2013). Soil salinization has several causes, including inadequate irrigation management, the excessive use of synthetic fertilizers, lack of a management plan for the elimination of Na in crop areas and the accumulation of Na ions due to insufficient irrigation under periods of low precipitation. In greenhouse crops, proper irrigation and fertilization practices are indispensable, and ions cannot be washed away by rain. Our results showed that the EC values had increased to detrimental levels by the end of the experiment. Large proportions of the ions used in the experiment were not consumed by the plant and were subsequently converted into potential environmental contaminants (Yasuor *et al.* 2013). Furthermore, Na ions and other ions that are not consumed have the capacity to generate saline soils, which have an EC of 4 dS m^{-1} (Shrivastava & Kumar 2015). This value is similar to the values obtained in our study (in dS m^{-1}): 3.68 for tomatoes, 3.38 for cucumbers, and 2.32 for lettuce.

High concentrations of NO_3-N in soil were found after completing the experiment. Among the crops, lettuce had the lowest amount of soil NO_3-N residue (46.7 mg kg^{-1}). Both the cucumbers and tomatoes, which represent crops characterized by high amounts of applied nitrogen fertilizer, were associated with high soil concentrations of not only NO_3-N (163 and 107 mg kg^{-1}, respectively) but also other elements, such as K, Ca, and (to lesser degrees) Na and Mg. Studies have shown that a high nitrate content in well water is associated with the excessive application of nitrogen fertilizers for agriculture (del Amor 2007). Therefore, in addition to avoiding N loss, it is crucial to increase the use efficiency of N ions and other ions that accumulate in soil to improve soil fertility and reduce environmental risks (Ju & Gu 2014).

O_2 and Na in nutrient solution

Hydroponic crops are characterized by dense root systems in small volumes of substrate with high rates of metabolic, respiratory, and growth activity (Soto-Bravo 2015); therefore, adequate oxygenation of the roots is critical for obtaining high yields. Our results revealed no significant difference in the concentration of dissolved oxygen at the entry point of the nutrient solution among the studied crops. Therefore, CPS is a good production method that not only can enhance the efficiencies of water and fertilizer consumption but also shows evidence of suitability regarding other indicators, such as oxygen concentration. On average, in the three production systems, dissolved oxygen levels higher than 8 ppm were observed in the nutrient solution (Figure 2). These levels are higher than

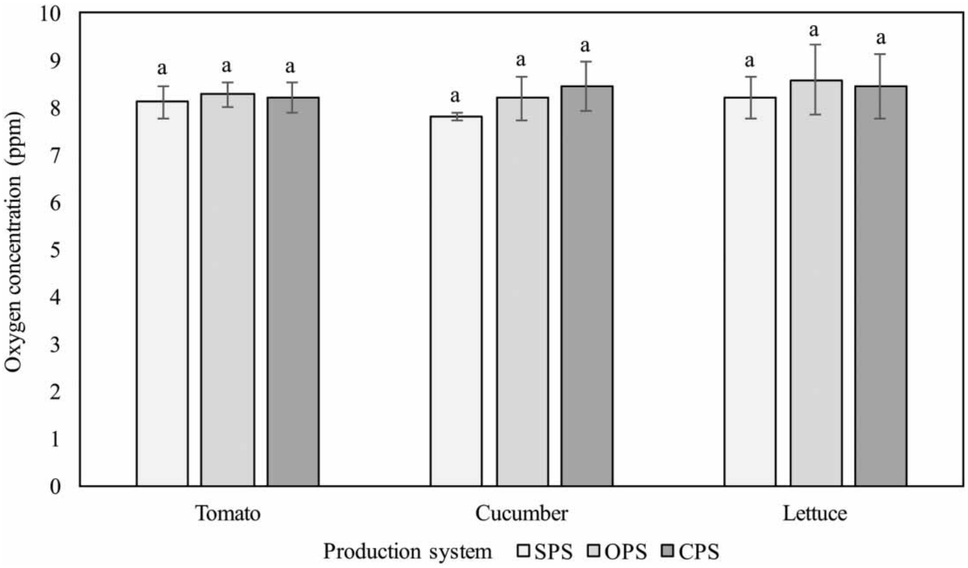

Figure 2 | Amount of dissolved oxygen (means ± standard error, $n = 20$) in the input nutrient solution for each crop. Bars with different letters within a crop are significantly different ($p < 0.05$).

the thresholds reported for tomatoes (Zheng *et al.* 2007), cucumbers (Gislerød & Adams 1983), and lettuce (Goto *et al.* 1996) of 5.3, 2.7, and 2.1 ppm, respectively, below which crop development is affected.

The concentration of Na in the nutrient input solution for both tomato and cucumber did not significantly differ among the production systems. However, in the drainage from the cucumber crop, which served to feed the lettuce crop in the CPS, an increase of 54.2% in Na was observed (Figure 3). We can conclude that part of the Na content in a polyculture should be absorbed by the plants, whereas another part should be discarded by way of periodic drainage to the subsequent crop. A similar pattern was observed in the

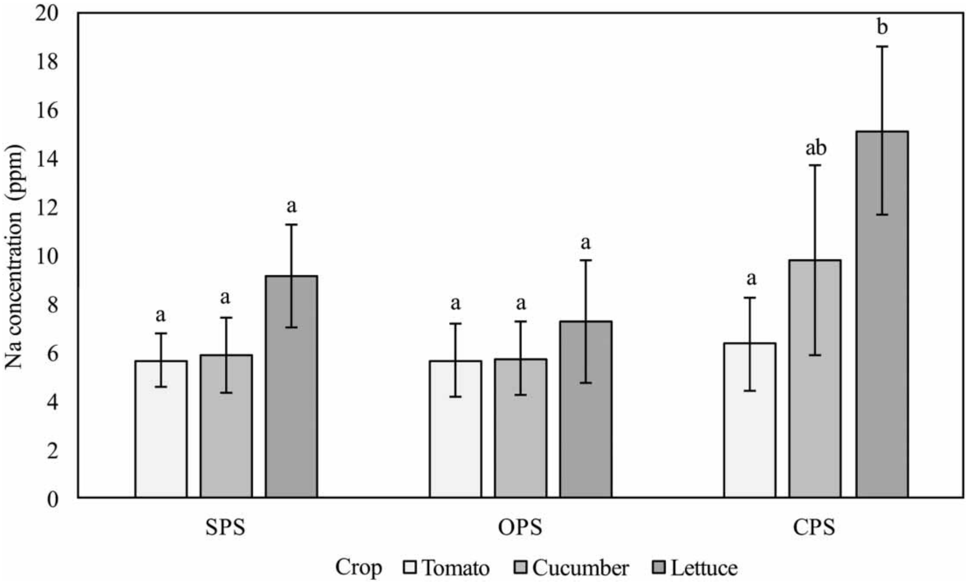

Figure 3 | Concentration of Na (mean ± standard error, $n = 50$) in the input nutrient solution by crop and by production system. Bars with different letters within a production system are significantly different ($p < 0.05$).

SPS. Relative to that before the crops were cultivated, the Na in soil increased by more than 4.7 times for the tomato crop, 5.7 times for the cucumber crop, and 4.2 times for the lettuce crop (Table 6). This finding is of concern not only because Na is a cation that displaces essential ions, such as K^+, Ca^{2+}, and Mg^{2+}, from the soil but also because it limits the absorption of elements, such as N, Ca, K, P, Fe, and Zn (Shrivastava & Kumar 2015). A saline nutrient solution in the soil or substrate negatively affects plant photosynthesis, chlorophyll content, and stomatal conductance (Netondo *et al.* 2004). In our results, shown in Table 2, we did not find significant differences in SPAD units of a crop among the different production systems. Therefore, we can be confident that the quantity of Na present in the last crop (lettuce) of the polyculture did not affect the crop physiologically. Depending on its genotype, lettuce is sensitive to salinity (Xu & Mou 2015); therefore, selecting a variety that can adapt to nutrient solutions with high Na concentrations would be beneficial for polyculture.

CONCLUSIONS

The results of the present study indicate that in polyculture, whether involving the crops used here or other crops, the use of 'drainage' nutrient solution for use with other crops can not only increase the yield per cubic meter of water used but also conserve fertilizer. Furthermore, when employing drainage water, fruit quality is comparable to that achieved with conventional production systems. In addition, by reusing drainage, contamination due to excessive salt contents in aquifers or soil can be reduced, and the water available for agriculture can be managed more conservatively.

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DECLARATIONS OF INTEREST

The authors declare no conflict of interest.

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