Technology in Horticulture

REVIEW

Open Access

https://doi.org/10.48130/tihort-0024-0002

Technology in Horticulture **2024**, 4: e005

Comparing resource use efficiencies in hydroponic and aeroponic production systems

Abishkar Regmi[1], Dario Rueda-Kunz[1], He Liu[1], Jonah Trevino[1], Shivani Kathi[1,2] and Catherine Simpson[1*]

[1] *Department of Plant and Soil Science, Texas Tech University, Lubbock, TX 79409, USA*

[2] *Department of Horticulture and Landscape Architecture, Oklahoma State University, Stillwater, OK 74077, USA*

* Corresponding author, E-mail: catherine.simpson@ttu.edu

Abstract

With depleting sources of fresh water, approaches must be taken to reduce the use of water in agricultural systems. Along with reduced usage, research should focus on using resources more efficiently. Hydroponic production systems offer higher resource use efficiency, such as water and fertilizer, compared to traditional agriculture systems. Notably, water usage can be reduced by more than 90% and fertilizer by 60% depending upon the system and crop. This review focuses on water and nutrient use efficiency of different crops in greenhouse production systems to further elucidate the current accomplishments and future needs in this research area. This is important because water and nutrient use efficiency is highly dependent upon multiple factors like type of crop, cultivars, environment, type of system used, nutrient concentration and form, flow rate of water, water depth, location, etc. Herein, nutrient film technique (NFT), deep-water culture, aeroponics, drip, and other systems were compared for different water and nutrient use efficiencies. Because different crops were used in these studies, direct comparison was limited, but we found that crop type and cultivars, NFT channel depth, and fertilization rate were among the most influential factors affecting nutrient use efficiency in hydroponic systems. Surprisingly, water use efficiency in aeroponic systems was greater when more nozzles were used. Aeroponic systems also showed greater water use efficiency when compared to NFT systems. Overall, this review highlights the resource use efficiency of different vegetable crops in hydroponic production systems and highlights opportunities for future research.

Citation: Regmi A, Rueda-Kunz D, Liu H, Trevino J, Kathi S, et al. 2024. Comparing resource use efficiencies in hydroponic and aeroponic production systems. *Technology in Horticulture* 4: e005 https://doi.org/10.48130/tihort-0024-0002

Introduction

Water scarcity is one of the important challenges threatening global crop production. According to the World Health Organization (WHO), 55 million people face the consequences of drought each year[1]. Meeting the food production demands over the next 50 years requires implementing improved water and resource management practices. Hence, many researchers are investigating drought-related challenges in crop production and developing techniques to reduce water usage, and increase the water and resource use efficiency[2]. Many new growers are moving away from traditional agriculture systems that require high inputs to alternative growing systems with high resource use efficiency[3]. Moreover, focus has shifted towards circular systems that reduce and conserve inputs and resources without compromising the overall yield[3]. Greenhouse and controlled environment production methods give us an opportunity to regulate and optimize the growing conditions for plants, but these systems still require nutrient and water inputs for production of high-quality crops[4]. So, it is important to prioritize efficient resource management practices that improve yield and quality of crops while minimizing wastage.

Water and nutrients can be used efficiently in greenhouse conditions as demonstrated by Ayarna et al.[5] and Verdoliva et al.[6]. Some of the more common techniques used in greenhouse production include drip irrigation, hydroponics and aeroponics[2,7]. Drip irrigation methods vary, but in general provide small amounts of water delivered on a regulated schedule to meet water demands of a crop. Hydroponics is defined as the technique of growing plants suspended in a nutrient rich water-based solution without using soil substrates[8] (Fig. 1). Alternatively, aeroponics is defined as growing of plants in air or mist environment without substrates where the plant roots are freely suspended in the air and are misted with nutrient solution periodically[9] (Fig. 2). However, there is no clear consensus on the definition and differences between hydroponics and aeroponics. Some classify vertical towers as a type of aeroponic system, instead of a type of nutrient film technique (NFT) system, even if mist systems are not used. Therefore, specific criteria must be established in research and academia to differentiate between hydroponics and aeroponics so that clearer guidelines and standards can be developed. The authors suggest that, while aeroponics is classified as a subcategory of hydroponics, it should be defined by the use of spray nozzles that spray roots with nutrient solution. Other guidelines may include a minimum or maximum droplet size, define the type of root suspension chamber, or provide criteria that exclude systems from being considered 'aeroponic'. Nonetheless, water and nutrient use efficiency of these systems remains a crucial factor in the success of both systems.

Water use efficiency (WUE) can be defined as the amount of water used by plants or plant systems relative to the amount of biomass produced[10]. For instance, higher water use efficiency indicates that less water is required to achieve a desired level of crop productivity, indicating a more efficient utilization of

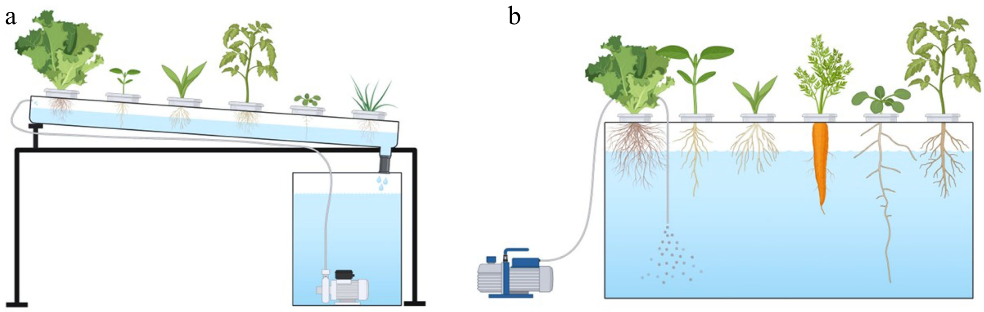

Fig. 1 Illustration of two hydroponic systems. (a) Nutrient film technique. (b) Deep water culture. Figure created by Dario Rueda Kunz using BioRender.com.

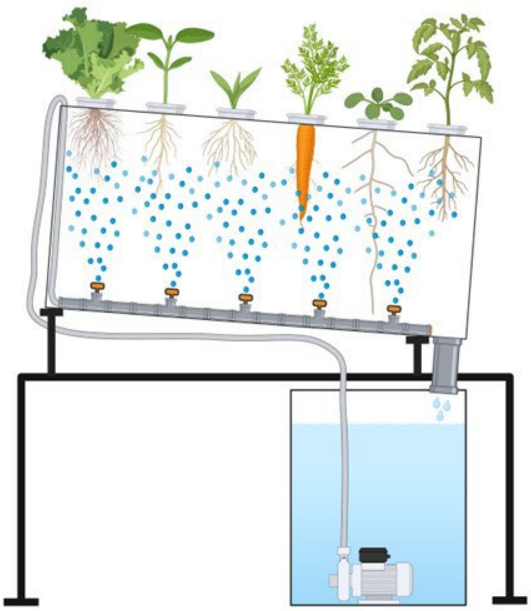

Fig. 2 Illustration of one type of aeroponic system with the reservoir outside the root chamber. Figure created by Dario Rueda Kunz using BioRender.com.

available water resources. Because water is a critical resource for plant growth, its availability and quality significantly impact crop quality and yield. Water is a limited resource that faces multiple demands, including municipal requirements, population needs, and agricultural usage. Growers in controlled environment agriculture (CEA), particularly in areas that are prone to drought or water restrictions, need sustainable and efficient ways to produce crops for high profit margins[11]. One of the key components of CEA is that the microclimate can be more easily controlled which makes it easier to modify plant needs, crop requirements, and resources used[7]. While WUE has been extensively researched in field systems, there are fewer studies that have explored WUE in CEA systems. These studies have found differing results when comparing different production systems and crops or cultivars. For example, in an experiment conducted by Shtaya & Qubbaj[10], lettuce (*Lactuca sativa*) grown in the NFT system had higher WUE than plants grown in soil and a mixture of peat moss/perlite. Similarly, cultivar also impacts the WUE as shown by El-Nakhel et al.[12], where WUE was higher in red Salanova lettuce as compared to green Salanova lettuce. Hence it is important to identify the CEA systems and cultivars that have higher WUE.

In addition to water, nutrients are also required for substrate culture hydroponic systems, such as soilless media (i.e. rockwool or coir) in CEA production because the substrate used contains little or no nutrients. Nutrient use efficiency (NUE) can be defined as the amount of nutrients such as nitrogen, phosphorus, and potassium used by the plants to produce biomass[13]. Most research that has been conducted focuses on nitrogen, as it is one of the major nutrients required by plants in the largest amounts[14]. While other nutrients are required, especially when absent from substrate, few studies on greenhouse crops regarding uptake or use efficiency have been conducted. Different production systems and factors also influence the NUE of crops. For example, cultivars impacted the NUE of tomato (*Solanum lycopersicum*) where higher NUE was found in Momotaro York as compared to Jaguar cultivars in study conducted by Ayarna et al.[5]. Many factors are known to affect the WUE and NUE in crops which include growing conditions and season, type of production systems used, and crop types. This further illustrates the necessity for more CEA research regarding WUE and NUE.

Ultimately, CEA has emerged as a sustainable and efficient method for growing crops in controlled and artificial environments. It is comprised of multiple technologies and advancements which enable the grower to optimize growing conditions and resources along with maximizing the crop yield and quality[4]. However, water and nutrients are critical components in CEA that have potentially high costs, limited availability, or quality in many regions. In this review, we will discuss the current state of knowledge on WUE and NUE in aeroponic and hydroponic systems, their challenges, and opportunities, as well as different strategies and methods for improvement.

Materials and methods

The articles for this review were collected from two databases: Google Scholar (https://scholar.google.com/) and the university library (Texas Tech University; www.depts.ttu.edu/library) which includes multiple scientific databases such as Agricola, Scopus and Web of Science. The search and screening were conducted following the systematic review guidelines outlined by the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) statement. The search criteria included relevant keywords and phrases in the title such as: 'water use efficiency', 'WUE', 'nutrient use efficiency', 'NUE', 'nitrogen use efficiency', 'aeroponics', 'hydroponics', 'nutrient film technique', 'NFT', 'deep water', 'raft system' and combinations thereof. After articles were compiled, references of these articles were evaluated to identify additional relevant papers. Research article exclusion criteria were language (other than English), full-text unavailable, CEA articles that did not study water or NUE, and articles with confounding factors that may have influenced the interpretation of this review. The initial search resulted in 98 articles based on relevance of search terms to titles. The authors then independently read the abstracts of the articles and further refined the relevant articles to 36. Then, the authors went through each article to determine if either NUE or WUE was evaluated and found 20 articles to be relevant to this review. Among the included articles, several calculations for WUE and NUE were found. Equations 1−5 (below) show these calculations.

Equations for WUE used in reviewed articles:

$$\mathrm{WUE}: \frac{Yield}{Solution\ consumed} \tag{1}$$

$$\mathrm{WUE}: \frac{Yield}{Applied\ irrigation} \tag{2}$$

$$\mathrm{WUE}: \frac{Yield}{Modelled\ water\ use} \tag{3}$$

Equations for NUE used in reviewed articles:

$$\mathrm{NUE}: \frac{Plant\ dry\ matter}{N\ Supply} \tag{4}$$

$$\mathrm{NUE}: \frac{Plant\ fresh\ weight}{Nutrient\ solution\ used} \tag{5}$$

The results of the search for individual factors WUE and NUE in different systems were presented in a tabular form. Each table has been individually constructed based on the needs of the given factor.

Results and discussion

Water use efficiency (WUE) in different hydroponics systems

Water use efficiency has been studied extensively in agronomic systems; however, controlled environment system studies have been limited. Only eight separate articles were found that studied vegetable crop WUE in different hydroponic systems (Table 1). Of these, three experiments took place in NFT systems, five were in drip hydroponic systems, two were in deep water culture, and one was in a deep flow technique system (Table 1). The majority of all systems (five of eight studies) grew tomatoes[5,6,15−17], and the remaining studied lettuce[10,12], coriander (*Coriandrum sativum*)[18], and cucumber (*Cucumis sativus*)[13]. The comparison between studies was limited by the different crop species, but also because of the different units and methods used in each study. While the units used varied by study, most authors reported WUE as g FW/L (FW = fresh weight) or kg/m^3 (Table 1), which are interconvertible. After converting to the same units (Table 1), the WUE was averaged across all crops to determine variability amongst crop species in each system. One study could not be converted to g/L because the authors reported the WUE as yield (g) over transpired water[6]. This was due to the method of analysis (i.e., weighing pots), and thus is not directly comparable. NFT and drip systems were used in more than one study on tomatoes within these systems. When taking an average between different systems on tomato, WUE was different between the hydroponic systems and ranged between 24.5 g FW/L for drip system[5,6,15,17], 9.15 g FW/L for deep water culture[6,16] and 33 g FW/L for NFT[15,17]. These findings show that, of the hydroponic systems studied, NFT had higher WUE than other systems and methods on tomato. However, we suspect that these findings may change as more crops and system designs are studied for WUE.

The literature was very diverse and revealed many factors that could affect WUE results (Table 1). WUE in hydroponic systems can be affected by cultivars[5,12], nutrient solution depth[18], circulation intervals[18], nutrient concentration[16] and fertigation levels[13]. For example, different cultivars of tomatoes showed different WUE in the literature. Ayarna et al., found that the tomato cultivar Jaguar doubled WUE in drip recirculating hydroponics (33 g FW/L), compared to Momotaro York, which had a WUE of 15 g FW/L. Similarly, Red Salanova, a lettuce cultivar, had higher WUE (92 g FW/L) than the Green Salanova cultivar (80 g FW/L)[5]. Furthermore, interactions between cultivar, species, or botanical variety and environment may also affect WUE. Valenzano et al.[15] found that beefsteak tomatoes showed a higher WUE than cherry tomatoes in both winter-spring and autumn-winter growing seasons. So far, these results indicate that physiological characteristics, not only between species, but cultivars will impact crop WUE.

Crop WUE is also highly dependent upon climate and season, which is rarely consistent between various systems, studies, regions, and individual researchers (Table 1). The five tomato studies that were evaluated in this review were not directly comparable because seasons, locations, and systems differed. Singh et al.[13] studied Kafka, Multistar, and PBRK-4 cucumber cultivars and their interaction with different irrigation levels and found that WUE of Multistar was statistically higher (44.1 kg/m^3) than PBRK-4 (40.3 kg/m^3). Furthermore, da Silva et al.[18] examined the impact of cultivar, nutrient solution depth, and circulation intervals in NFT on coriander and determined that 0.25 h intervals and 0.02 m solution depth showed a significant influence on WUE at 20 and 25 d after transplant. However, the study did not address variations in WUE across different cultivars. Fertilizer form is also an important factor when considering WUE, because fertilization directly influences yields. Contrary to soil cultivation, in hydroponics, water is the only medium through which plants can absorb applied nutrients. This, in turn, affects fertilizer use, availability, and absorption of nutrients. Claussen[16] found that fertilizer form and rate significantly impacted WUE in tomato where treatments with ammonium had more varying impacts on WUE than nitrate. This further illustrates that WUE is affected by multiple factors that must be considered when evaluating efficiency of hydroponic systems.

Nutrient use efficiency (NUE) in different hydroponics systems

Nutrient use efficiency is one of the most crucial factors to consider when growing plants in controlled environments. The literature search revealed three papers that studied the NUE (i.e. nitrogen) of crops grown in hydroponic systems. In the literature, most researchers have used NUE interchangeably with nitrogen use efficiency, as they primarily focused on nitrogen as the nutrient of interest. Therefore, this review will focus on nitrogen in NUE. Nitrogen is the mineral nutrient needed in the highest amounts for plant growth and development and makes up the highest amount of mineral nutrients present in plants[19]. As a result, adequate amounts of nutrients must be applied to the plants, but different growing conditions affect

Table 1. Studies that evaluated water use efficiency (WUE) in different hydroponic systems.

System	Location	Crop	Treatment	Equation	WUE	Unit	Conversion (g Fw/L)	Main findings	Ref.
Drip recirculating hydroponics	Kashiwanoha, Japan	Tomato (*Solanum lycopersicum*) cv. Momotaro York	Different cultivars	Fruit weight/total water uptake per plant	0.015	kg/kg	15	WUE was dependent on cultivar.	[5]
		Tomato (*Solanum lycopersicum*) cv. Jaguar			0.033		33		
NFT system	Naples, Italy	Lettuce (*Lactuca sativa*) cv. Red Salanova	Different cultivars	FW/Volume of water consumed	92	g/L	92	WUE was dependent on cultivar.	[12]
		Lettuce (*Lactuca sativa*) cv. Green Salnova			80.8		80.8		
Deep flow technique	Bahia, Brazil	Coriander (*Coriandrum sativum*) cv. Tabocas & Verdao	Two Nutrient solution depths: 0.02 and 0.03 m Three recirculation intervals: 0.25, 12 and 24 h	FW/Total water consumed	29.43 @ 15 min interval	g/L	29.43	Recirculation interval significantly affected WUE, with higher WUE at 15 min intervals.	[18]
					25.93 @ 2 cm		25.93	A 2 cm depth of water had higher WUE.	
Closed loop- NFT	Bari, Italy	Tomato (*Solanum lycopersicum*) cv. Diana, Jama (Beef steak) Naomi, Conchita (Cherry)	NFT	Fruit yield/Water supplied	31–45	g/L	38	NFT had higher WUE. Cultivation system and tomato type were significant. WUE varied among different seasons.	[15]
Open loop- drip fertigation			Rockwool		23–25		24		
Soil			Soil		31–37		34		
Deep water culture	Grossbeeren, Germany	Tomato (*Lycopersicon esculentum*) Mill. Cv. Counter	Nutrient form and concentration	DW/water used	1–3.5	g/kg	2.25	Nutrient form and concentration affected WUE.	[16]
Drip system	Punjab, India	Cucumber (*Cucumis sativus*) var. Kafka, Multistar & PBRK-4	Three fertigation levels (100%, 85% and 70%)	Irrigation WUE: Yield/Irrigation water applied	Irrigation WUE: 34.5–51.4	kg/m^3	42.95	Both variety and nutrient solution significantly affected WUE.	[13]
				Crop WUE: Yield/Crop Water use	Crop WUE: 120.6–179.9		150.25		
Closed system-NFT	Ahvaz, Iran	Tomato (*Solanum lycopersicum*) cv. V4-22 & Amira	Closed system	Fruit yield/cubic meter water applied	Water productivity: 33.7 Water productivity biomass: 48.91	kg/m^3	27.91	Water productivity was lower in the closed hydroponic system.	[17]
Open system-drip			Open system		Water productivity: 21.84. Water productivity biomass: 34.42		41.88		
Drip system	Wales, United Kingdom	Tomato (*Solanum lycopersicum*) cv. Forticia F1	Drip	FW fruit/L of transpired water	0.0072–0.0099	kg/L	8.55	Hydroponic systems had higher WUE than soil.	[6]
Deep water culture			Deep water		0.0059–0.0124		9.15		
soil			Soil		0.0035–0.0044		3.95		
NFT	Tulkarm, Palestine-	Lettuce (*Lactuca sativa*)	Four growing methods	DW/kg water applied	121	kg/m^3	121	WUE was higher in NFT.	[10]

FW – fresh weight, DW – dry weight, NFT – nutrient film technique.

the efficiency of applied nutrients to be taken up and converted to plant biomass[20]. Specifically, factors like temperature, plant species and cultivars, water quality, flow rates, type of systems and ratio of nutrients applied have been found to affect the NUE[10,11]. Three studies were found that determined the NUE in hydroponic production of various crops (Table 2). Of those, one study was conducted in NFT system[14] and two in drip system[5,13]. The NUE varied among the different studies likely due to different equations for calculating NUE (Table 2, Eqns 1−3). Among the other factors that contribute to differences in NUE are the types of crops studied and the systems used (Table 3). In the NFT hydroponic system, NUE was affected by the flow rate. For example, Baiyin et al.[14], found that the NUE of Swiss Chard (*Beta vulgaris L.*) ranged from 20−25 g/g DW in NFT when different flow rates of nutrient solution (2 L/min, 4 L/min, 6 L/min and 8 L/min) were used. The Swiss Chard had a higher NUE of approximately 25 g/g DW at 8 L/min flow rate and lower NUE of 21 g/g DW at 2 L/min flow rate. Alternatively, NUE of tomato grown in drip system ranged from 112−221 g/g FW in a drip system in an experiment conducted by Ayarna et al.[5] . In this study, Ayarna et al.[5] compared two tomato cultivars Jaguar and Momotaro York and found that Jaguar had two times higher NUE than Momotaro York at 70 d after transplanting (221.1g/g FW and 111.9 g/g FW, respectively). Furthermore, in a study conducted by Singh et al.[13] on cucumber grown in a drip system, NUE of cultivar Multistar was statistically higher (266.7 g/plant) than PBRK-4 (243.1 g/plant). In the same study, NUE compared among different fertigation levels calculated based on the total nutrients applied ranged from 229−282 g/g FW[13]. However, the use of fresh weight and dry weight, and different equations to calculate NUE in these studies makes the comparison difficult. While we can provide a broad overview and perspective of NUE in different systems, we cannot directly compare the systems. However, in most of the studies, the primary factors affecting the NUE were cultivar, species and fertigation levels[5,13,14]. Additionally, the limited number of studies, variability in crops, systems, and environment limited the comparison between studies and made identification of primary factors that affect NUE in hydroponic systems difficult. Therefore, it is essential that future research include NUE as a component to compare system and plant performance.

Water use efficiency in aeroponics systems

Aeroponic systems studies regarding WUE are even more limited than the other hydroponic systems. Aeroponic systems vary widely in design and definition, which also made comparison of these systems challenging. While some consider systems that leave roots suspended in the air and circulate nutrient solution to be aeroponic systems, we limited our definition to systems that utilized nozzles to aerosolize nutrient solutions and spray roots. Following these guidelines, only five separate articles were found that studied vegetable crop WUE in aeroponic systems (Table 3). Three experiments were performed on lettuce[22,23,25], one on cucumber[21], one on celery (*Apium graveolens*)[23], and one on onion (*Allium cepa*)[24]. Half of these studies grew the crops in aeroponic towers, and the other half used root chamber designs (Table 3). The difference between these two designs were orientation of root chambers, and the location of the nutrient solution reservoir (directly attached to the system or in a separate reservoir). In this context, vertical aeroponic towers are oriented vertically and have attached reservoirs for circulating the nutrient solution[21,23]. Root chamber aeroponic units are oriented horizontally and typically have an external reservoir for circulating the nutrient solution[22,24,25]. The units used for WUE by the authors were either g FW/L or kg/m^3, which are interconvertible as mentioned previously. After compiling all the experiments (Table 3), we averaged the WUE across all crops to determine variability amongst the crop species in these systems. The WUE ranged between 11 and 98 g/L amongst crops and 8 to 111.8 g/L for root chamber systems and 3.02 to 142.91 g/L for nutrient solution reservoirs (Table 2). This wide range of WUE demonstrates the variability in systems, crops, and how important standardization can be for comparison. For example, in an aeroponic tower, the average WUE for cucumber was 97.94 g/L[21] and celery was 11.65 g/L[23]. Furthermore, Jamshidi et al. found the duration of nutrient and water application as the main factors affecting the production of vegetables in aeroponics[21]. Alternatively, onion grown using root chambers in an aeroponic with floating and aggregate growing system, had an average bulb WUE of 25.36 g/L[23]. Hence, aeroponic systems were not as successful as other systems and the authors attribute this to the entanglement of new roots with older roots caused by the spray liquid[21]. This occurs depending on the position of the nebulizers applying the nutrient solution and frequency of irrigation[24]. Lettuce was extensively studied in different aeroponic construction configurations, with two experiments in root chambers[22,25] and one in an aeroponic tower[23]. However, the average WUE for all the lettuce experiments was not comparable since the authors used different equations to determine WUE. Instead, we separated the studies based on the equation used to compute WUE (Eqns 1−3). This was a key

Table 2. Studies conducted on nutrient use efficiency (NUE) in hydroponic systems.

System	Location	Crop	Treatment	Equation	NUE	Unit	Main Findings	Ref.
NFT (flow of nutrients)	Totori, Japan	Swiss Chard (*Beta vulgaris* spp. Cicla)	Different flow rates - 2, 4, 6 and 8 L/min	Dry wt./nutrient uptake of whole plant	20–25	g/g DW	Highest NUE at 8 L/m flow rate	[14]
Drip recirculating hydroponics	Kashiwanoh a, Japan	Tomato (*Solanum lycopersicum*) cv. Momotaro York	Different cultivars	Ratio of fruit fresh FW/total nitrogen uptake per plant at first harvest	111.9	kg/FW kg	Jaguar had greater NUE than Momotaro York	[5]
		Tomato (*Solanum lycopersicum*) cv. Jaguar			221.1			
Drip system	Punjab, India	Cucumber (*Cucumis sativus*) var. Kafka, Multistar & PBRK-4	Three fertigation levels and three varieties	Yield/nutrient applied	229.6–281.8	g/plant	Fertigation level affected NUE	[13]

NFT – nutrient film technique.

Table 3. Studies conducted on water use efficiency (WUE) in aeroponic systems.

System	Location	Crop	Treatment (T)	Equation	Unit	WUE	Main findings	Ref.
Aeroponic tower	Kerman, Iran	Cucumber (*Cucumis sativus*)	Different flow rates and spray duration: 125 mL/min, 10 min	*WUE* = (*YS*)/∑WU (Total water consumed)	kg (total yield)/m^3	94.4	Applying insufficient or excess water affected WUE more than changing the application duration. The optimum rate was 233.59 mL/min with an application time of 16.06 min.	[21]
			125 mL/min, 15 min			98.8		
			125 mL/min, 20 min			98.2		
			250 mL/min, 10 min			109.2		
			250 mL/min, 15 min			111.8		
			250 mL/min, 20 min			105.8		
			375 mL/min, 10 min			91.1		
			375 mL/min, 15 min			87.2		
			375 mL/min, 20 min			85		
Root chambers	Benha, Egypt	Lettuce (*Lactuca sativa*)	Different flow rates: 0.5 L/h	WUE = CY/CWU	kg (crop plant yield)/m^3 (modelled water uptake)/plant	3.87	After the 50 d growing period, higher WUE with 0.5 L/h flow rate (3.87 kg/m^3). Lowest at 1.5 L/h rate (3.02 kg/m^3). A higher flow rate gave longer roots and reduced fresh biomass.	[22]
			1 L/h			3.47		
			1.5 L/h			3.02		
Aeroponic tower	Cairo, Egypt	Lettuce (*Lactuca sativa*)	Number of sprinklers: 1 nozzle Mini sprinkler	WUE = (total fresh yield, kg)/(total applied irrigation water, m^3)	kg fresh yield/m^3 water	8	Adding nozzles resulted in higher WUE in both crops because higher biomass production was achieved.	[23]
			2 nozzle Mini sprinkler			8.8		
			4 nozzle mini sprinkler			11.2		
		Celery (*Apium Graveolens*)	Number of sprinkler: 1 nozzle mini sprinkler	WUE = (total fresh yield, kg)/(total applied irrigation water, m^3)	kg fresh yield/ m^3 water	9.75		[23]
			2 nozzle mini sprinkler			12.4		
			4 nozzle mini sprinkler			12.8		
Root chambers	Kalamata, Greece	Onion (*Allium cepa*)	Irrigation frequency: Daily 1 min ON/3 min OFF	WUE = g (Bulb FW)/L (Nutrient solution consumed)	g/L	25.36	Aeroponics outperformed an NFT system in WUE, plant biomass, bulb size, and total yield.	[24]
Root chambers	Changchun, China	Lettuce (*Lactuca sativa* L. *var. ramosa Hort*)	Different nutrient solution and pH: T1: total nutrient solution, pH 5	WUE = g (Total yield fresh weight)/L (Total water use). Total water use = sum of cumulative water uptake and water loss	g FW/L	29.68	Half nutrient solutions with pH of 6 produced higher WUE. EC based fertilization method resulted in the highest WUE even in low pH.	[25]
			T2: half nutrient solution, pH 5			41.88		
			T3: adjusting EC, pH 5			127.8		
			T4: total nutrient solution, pH 6			30.81		
			T5: half nutrient solution, pH 6			91.08		
			T6: adjusting EC, pH 6			142.91		
			T7: total nutrient solution, pH 7			35.74		
			T8: half nutrient solution, pH 7			63.57		
			T9: adjusting EC, pH 7			130.19		

EC – Electrical conductivity, CY – Crop yield, CWU – Crop water use.

issue throughout all WUE studies evaluated, because consumed, applied, and calculated water use are different concepts which will impact WUE. When water use was modeled as a function of leaf area index and daily radiation as shown in Eqn 3, the WUE averaged 3.45 g/L[22]. On the other hand, WUE calculated using total applied irrigation water as shown in Eqn 2, had an average of 9.3 g/L[23]. The last study in our opinion, is more logical for a closed soilless production system, in which the authors use the used solution to compute WUE (Eqn 1) and had an average of 77.07 g/L[25]. This is important because changing nutrient solutions will affect WUE, because that volume of solution is being removed and therefore 'used', ultimately decreasing WUE because the total volume applied isn't necessarily consumed by the plant. The study by Chabite et al. shows that the method of replacing the nutrient solution (dilution and adjustment of the solution) and the pH of the solution are the most important factors that affect WUE[25]. Thus, the application or utilization of nutrient solutions in various methods might have a detrimental effect on WUE and its calculation. This further illustrates the importance of consistent measurements and methodologies when designing new studies and formulating new nutrient solutions.

Nutrient use efficiency in aeroponics systems

The literature search indicated limited studies on NUE of aeroponic systems. In general, there are various applications of NUE, such as potassium use efficiency, phosphorus use efficiency, and so on. However, as mentioned above, similar to hydroponics production, nitrogen is the most frequently reported nutrient when it comes to NUE. To date, only five articles have been identified that specifically reported NUE results focusing on nitrogen. The typical equation for four out of five of these studies was Eqn 4, except for the water cycling lettuce study, that used Eqn 5 (Table 4). However, these studies primarily focused on other research aspects, while reporting NUE of their aeroponic crops as a secondary objective in their articles. Out of the five articles, three of them were authored by Tiwari et al.[26−28] and focused specifically on seed potato cultivation. In these studies, Tiwari et al.[26−28] conducted several potato growth trials to assess NUE of different varieties under varying levels of applied nitrogen. In the first study, Tiwariet al.[26] observed two potato varieties, namely *Kufri gaurav* and *Kufri jyoti*, and found that *Kufri gaurav* exhibited higher efficiency in nitrogen uptake. In this study, two nitrogen amounts were applied: a high amount, and a low amount. For *Kufri gaurav*, the high amount of nitrogen resulted in a NUE of approximately 0.15 g/g, while the low amount of nitrogen showed 2.1 g/g. However, for *Kufri jyoti*, the high amount of nitrogen showed a NUE at 0.2 g/g, while the low amount of nitrogen had a NUE of 1.6 g/g. In the subsequent study, Tiwari et al.[27] observed phenotyping of *Kufri gaurav* in more detail. They maintained the same rates of nitrogen as in the previous study and found that the low nitrogen supply yielded a greater NUE value of approximately 0.85 g/g while the high nitrogen showed a value approaching zero. In the third study by Tiwari et al.[28], 56 different seed potato varieties were compared and a NUE of 0.28 g/g was recorded for the lowest, and 2.95 g/g for the highest. Gaudin et al.[29] conducted similar research comparing modern corn varieties with earlier varieties grown in an aeroponic system. The results revealed that the modern corn variety had a NUE of 2.1 g/g for the high nitrogen treatment, and a 3.1 g/g for the low nitrogen treatment. Alternatively, the older teosinte corn showed an NUE of 3.6 g/g for the high nitrogen treatment, and a 5.5 g/g for the low nitrogen treatment. These findings demonstrate the importance of nutrient concentration in the solution and its impact on NUE. Furthermore, it was consistently proved that lower concentrations of nutrients in solution resulted in higher NUE, suggesting the potential for improving sustainability in aeroponic systems through nutrient management. In another study, Chabite et al. investigated how water cycling techniques in aeroponic nutrient reservoirs can influence NUE[25]. Chabite et al. grew nine lettuce plants in nine different treatments, involving various water cycling methods and pH levels[25]. The NUE for these plants ranged from 5.17 to 16.53 g/L. Notably, the treatment resulting in NUE of 16.53 g/L had a pH of 6 and replaced half of the nutrient solution every 10 d. These results highlight the influence of solution pH and management techniques, such as water cycling, on NUE in aeroponic systems.

Furthermore, similar to hydroponics, the lack of consistency among studies regarding cultivars, environmental conditions, practices, and methodology poses challenges in determining the best practices for NUE in aeroponic systems. One particular difficulty arises from variations in reporting NUE, including differences in the formula used for NUE calculations. Four of the five studies reported NUE based on dry weight, while one study used fresh weight. Establishing standards or guidelines for calculating NUE could greatly benefit researchers by promoting consistency across all studies thereby facilitating relevant comparisons.

Conclusions

While there has been a limited amount of research on water and nutrient use efficiency in different CEA production systems, we have seen that these systems are conducive for efficient use of water and nutrients. Though discrepancies have been found between different research studies, the results are promising with regards to resource efficiency in controlled environment production. Improved resource use efficiencies can be attributed to reduced nutrient leaching, precisely controlled nutrient delivery, reduced competition with weeds for resources, low pest infestation rates, etc[30]. However, there is a high rate of variability between environments, cultivars, species, and production systems. All crops have different requirements and demands for water and nutrients, which highlights the necessity for more research on a wide variety of crops in different environments. There is much remaining to be learned with regards to water and nutrient use efficiency in CEA production systems, yet these technologies also hold much promise for the future.

Studying crops in controlled environments using different hydroponic production systems is challenging due to the technology involved and equipment used. This equipment can be assembled in different ways, and there are few guidelines for standardization amongst systems. For example, aeroponic systems are not clearly defined in literature; with some researchers using aerosolized nutrient solution sprays and others using roots suspended in air as their qualifiers. While we have provided some suggestions for defining criteria, we encourage researchers to include more thorough details in the future when describing these systems to allow for a better understanding of the research being conducted and guidelines to be developed. Research is being conducted on CEA worldwide,

Table 4. Studies conducted on nutrient use efficiency (NUE) in aeroponics.

System	Location	Crop	Treatment	Equation	Units	NUE	Main findings	Ref.
Root chamber	Shimla, India	Potato (*Solanum tuberosum* var. Kufri Gaurav)	T1: 0.75 mM N with 30 s ON and 5 min OFF T2: 7.5 mM N with 30 s ON and 5 min OFF	NUE = Plant dry matter accumulation/crop N supply	g/mM	~0.85 ~ 0	Lower nitrogen applied resulted in higher NUE	[26]
Root chamber	Shimla, India	Potato (*Solanum tuberosum* var. Kufri Jyoti)	T1: 0.75 mmol/L N with 30 s ON and 5 min OFF T2: 7.5 mmol/L N with 30 s ON and 5 min OFF	NUE = Plant dry matter accumulation/crop N supply	g/g	~1.6 ~0.20	Kufri Gaurav had the highest NUE when the 0.75 mmol/L supply of N was applied	[27]
		Potato (*Solanum tuberosum* var. Kufri Gaurav)	T1: 0.75 mmol/L N with 30 s ON and 5 min OFF T2: 7.5 mmol/L N with 30 s ON and 5 min OFF			~2.1 ~ 0.15		
Root chamber	Shimla, India	Potato (*Solanum tuberosum*)	T: 56 seed potato varieties. 2 mM N with 30 s ON and 5 min OFF	NUE = Plant dry matter accumulation/crop N supply	g/g	0.28 (Kufri Shailja) to 2.95 (Kufri Frysona)	Kufri Frysona had the highest NUE of all potato seed varieties tested	[28]
Root chamber	Ontario, Canada	Corn (*Zea mays*)	T1: Low N with 10 s ON and 50 s OFF T2: High N with 10 s ON and 50 s OFF	NUE = shoot dry weight/ N supply	g/mmol	3.1 2.1	The Teosinte variety of corn had higher NUE when using low N in an aeroponic system when compared to modern day corn using the same amount of N treatments.	[29]
		Teosinte (*Zea mays* spp. Parviglumis)	T1: Low N with 10 s ON and 50 s OFF T2: High N with 10 s ON and 50 s OFF			5.5 3.6		
Root chamber	Changchun, China	Lettuce (*Lactuca sativa* L. var. ramosa Hort)	T1: total nutrient solution, pH 5 T2: half nutrient solution, pH 5 T3: adjusting EC, pH 5 T4: total nutrient solution, pH 6 T5: half nutrient solution, pH 6 T6: adjusting EC, pH 6 T7: total nutrient solution, pH 7 T8: half nutrient solution, pH 7 T9: adjusting EC, pH 7	NUE = Total yield dry matter/Total nitrogen use (gDM/N)	gDM N	7.84 5.17 11.12 6.75 16.53 13.82 7.87 8 10.68	T5 (half nutrient solution at pH 6) was found to have the greatest NUE.	[25]

but access and availability of supplies is variable. Therefore, studies should consider how their system could vary from those conducted elsewhere when reporting results. The authors realize that research should be accessible even if environmental conditions are not strictly controlled, and that the results are still significant which can contribute to the overall body of research. However, variability in systems can have environmental impacts as inefficient systems can generate more waste and have higher energy consumption. The sustainability of the controlled environment must be considered in order to optimize efficiency. Thus, care must be taken to determine where efficiencies can be improved. Further challenges will vary based on location, research facility, supplies, equipment, and many other factors, but consistent reporting of findings is essential for comparison and building scientific knowledge.

Research examined in this review has shown that overall, aeroponic and other hydroponic systems can improve this efficiency, but results are inconsistent across systems and crops. This is partially due to the wide variety of systems used, individual characteristics of cultivars and crop species, environment, and growing conditions. We suggest that, in light of these findings, researchers should focus on evaluating crops using more standardized methods and units, so that the results are more comparable to others and help us more fully understand water and nutrient use efficiency of different crops grown in the different systems. While innovation and novel research is essential for the future of CEA, this can still be achieved by using consistent methods and equations. This review provides a baseline for determining and selecting the most suitable methods and techniques for efficient resource use in horticultural crop production.

Author contributions

The authors confirm contribution to the paper as follows: study conception and design: Simpson C, Regmi A, Rueda-Kunz D, Trevino J, Liu H; data collection: Simpson C, Regmi A, Rueda-Kunz D, Trevino J, Liu H, Kathi S; analysis and interpretation of results Simpson C, Regmi A, Rueda-Kunz D, Trevino J, Liu H, Kathi S; draft manuscript preparation: Simpson C, Regmi A, Rueda-Kunz D, Trevino J, Liu H, Kathi S. All authors reviewed the results and approved the final version of the manuscript.

Data availability

The datasets generated during and/or analyzed during the current study are available from the corresponding author upon reasonable request.

Acknowledgements

The authors would like to thank and acknowledge the Urban Horticulture and Sustainability Group at Texas Tech University for their insight and knowledge about the subject. The authors would also like to acknowledge Vikram Baliga for providing space for this project to be conceptualized and written. Finally, the authors would like to thank Kamron Newberry for the suggestion to write this review paper.

Conflict of interest

The authors declare that they have no conflict of interest. Catherine Simpson is the Editorial Board member of *Technology in Horticulture* who was blinded from reviewing or making decisions on the manuscript. The article was subject to the journal's standard procedures, with peer-review handled independently of this Editorial Board member and the research groups.

Dates

Received 2 November 2023; Accepted 1 February 2024; Published online 12 March 2024

References

1. World Health Organization. *Drought*. www.who.int/health-topics/drought#tab=tab_1 (Retrieved July 27, 2023)
2. Sharma N, Acharya S, Kumar K, Singh N, Chaurasia OP. 2018. Hydroponics as an advanced technique for vegetable production: an overview. *Journal of Soil and Water Conservation* 17:364–71
3. Gruda NS. 2019. Increasing sustainability of growing media constituents and stand-alone substrates in soilless culture systems. *Agronomy* 9:298
4. Walters KJ, Behe BK, Currey CJ, Lopez RG. 2020. Historical, current, and future perspectives for controlled environment hydroponic food crop production in the United States. *HortScience* 55:758–67
5. Ayarna AW, Tsukagoshi S, Oduro Nkansah G, Lu N, Maeda K. 2020. Evaluation of tropical tomato for growth, yield, nutrient, and water use efficiency in recirculating hydroponic system. *Agriculture* 10:252
6. Verdoliva SG, Gwyn-Jones D, Detheridge A, Robson P. 2021. Controlled comparisons between soil and hydroponic systems reveal increased water use efficiency and higher lycopene and β-carotene contents in hydroponically grown tomatoes. *Scientia Horticulturae* 279:109896
7. Niu G, Masabni J. 2018. Plant production in controlled environments. *Horticulturae* 4:28
8. Sánchez E, Di Gioia F, Flax N. 2021. *Hydroponics systems and principles of plant nutrition: essential nutrients, function, deficiency, and excess*. Penn State Extension Fact Sheet. pp. 1–5. https://extension.psu.edu/hydroponics-systems-and-principles-of-plant-nutrition-essential-nutrients-function-deficiency-and-excess
9. Niu G, Masabni J. 2022. Hydroponics. In *Plant Factory Basics, Applications and Advances*, eds Kozai T, Niu G, Masabni J. Amsterdam: Elsevier. pp. 153–66 https://doi.org/10.1016/b978-0-323-85152-7.00023-9
10. Shtaya MJY, Qubbaj T. 2022. Effect of different soilless agriculture methods on irrigation water saving and growth of lettuce (*Lactuca sativa*). *Research on Crops* 23:156–62
11. Frasetya B, Harisman K, Ramdaniah NAH. 2021. The effect of hydroponics systems on the growth of lettuce. *IOP Conference Series: Materials Science and Engineering* 1098:042115
12. El-Nakhel C, Giordano M, Pannico A, Carillo P, Fusco GM, et al. 2019. Cultivar-specific performance and qualitative descriptors for butterhead salanova lettuce produced in closed soilless cultivation as a candidate salad crop for human life support in space. *Life* 9:61
13. Singh M, Singh G, Singh J. 2019. Nutrient and water use efficiency of cucumbers grown in soilless media under a naturally ventilated greenhouse. *Journal of Agricultural Science and Technology* 21:193–207
14. Baiyin B, Tagawa K, Yamada M, Wang X, Yamada S, et al. 2021. Effect of substrate flow rate on nutrient uptake and use efficiency in hydroponically grown Swiss chard (*Beta vulgaris* L.ssp. *cicla* 'seiyou shirokuki'). *Agronomy* 11:2050
15. Valenzano V, Parente A, Serio F, Santamaria P. 2008. Effect of growing system and cultivar on yield and water-use efficiency of greenhouse-grown tomato. *The Journal of Horticultural Science and Biotechnology* 83:71–75
16. Claussen W. 2002. Growth, water use efficiency, and proline content of hydroponically grown tomato plants as affected by nitrogen source and nutrient concentration. *Plant and Soil* 247:199–209
17. Fayezizadeh MR, Ansari NAZ, Albaji M, Khaleghi E. 2021. Effects of hydroponic systems on yield, water productivity and stomatal gas exchange of greenhouse tomato cultivars. *Agricultural Water Management* 258:107171
18. da Silva MG, Soares TM, Gheyi HR, Costa IP, Vasconcelos RS. 2020. Growth, production and water consumption of coriander grown under different recirculation intervals and nutrient solution depths in hydroponic channels. *Emirates Journal of Food and Agriculture* 32:281–94
19. Bloom AJ. 2015. The increasing importance of distinguishing among plant nitrogen sources. *Current Opinion in Plant Biology* 25:10–16
20. Uchida R. 2000. Essential nutrients for plant growth: nutrient functions and deficiency symptoms. In *Plant Nutrient Management in Hawaii's Soils, Approaches for Tropical and Subtropical Agriculture*, eds Silva JA, Uchida R. College of Tropical Agriculture and Human Resources, University of Hawaii at Manoa. pp. 31–55. www.ctahr.hawaii.edu/oc/freepubs/pdf/pnm3.pdf
21. Jamshidi AR, Moghaddam AG, Ghoraba FM. 2020. Simultaneous optimization of water usage efficiency and yield of cucumber planted in a columnar aeroponic system. *International Journal of Horticultural Science and Technology* 7:365–75
22. Ali MM, Khater ESG, Ali SA, El-Haddad ZA. 2017. *Comparison between hydroponic and aeroponic systems for lettuce production*. Thesis. Benha University, Egypt.
23. Bedair OM. 2017. Vertical-farming irrigation system appropriate for lettuce and celery crops. *Misr Journal of Agricultural Engineering* 34:1701–18
24. Mouroutoglou C, Kotsiras A, Ntatsi G, Savvas D. 2021. Impact of the hydroponic cropping system on growth, yield, and nutrition of a Greek sweet onion (*Allium cepa* L.) Landrace. *Horticulturae* 7:432
25. Chabite IT, Zhang L, Yao N, Fu Q, Yu H. 2017. Mode of managing nutrient solution based on N use efficiency for lettuce (*Lactuca sativa* L.). *Journal of Food Science and Engineering* 7:29–37
26. Tiwari JK, Devi S, Buckseth T, Ali N, Singh RK, et al. 2020. Precision phenotyping of contrasting potato (*Solanum tuberosum* L.) varieties in a novel aeroponics system for improving nitrogen use efficiency: in search of key traits and genes. *Journal of Integrative Agriculture* 19:51–61
27. Tiwari JK, Buckseth T, Devi S, Varshney S, Sahu S, et al. 2020. Physiological and genome-wide RNA-sequencing analyses identify

candidate genes in a nitrogen-use efficient potato cv. Kufri Gaurav. *Plant Physiology and Biochemistry* 154:171−83

28. Tiwari JK, Buckseth T, Singh RK, Zinta R, Thakur K, et al. 2022. Aeroponic evaluation identifies variation in Indian potato varieties for root morphology, nitrogen use efficiency parameters and yield traits. *Journal of Plant Nutrition* 45:2696−709
29. Gaudin ACM, McClymont SA, Raizada MN. 2011. The nitrogen adaptation strategy of the wild teosinte ancestor of modern maize, *Zea mays* subsp. *parviglumis*. *Crop Science* 51:2780−95
30. Kozai T, Niu G, Takagaki M. 2015. *Plant Factory An Indoor Vertical Farming System for Efficient Quality Food Production*. Cambridge: Academic Press. 423 pp.