RESOURCE INNOVATION INSTITUTE

Best Practices Guide
Water Circularity

for Controlled Environment Agriculture (CEA) Operations

A Best Practices Guide for CEA Producers

JUNE 2023

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ACEEE American Council for an Energy-Efficient Economy

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In memory of Marc van Iersel, Dooley Professor at the University of Georgia, Department of Horticulture, whose research on reducing greenhouse water and energy consumption left the planet a little better than he found it.

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Overview

As a member or student of the controlled environment agriculture (CEA) industry, you may feel like it is hard to find objective guidance on sustainability projects. The market is dynamic, technology and scientific discoveries are advancing, and there are complex terms to know for every strategy. Designing water recycling systems for a highly productive and resource-efficient facility can understandably be a challenge.

Resource Innovation Institute is here to help. As an objective, data-driven non-profit organization, RII measures, verifies, and celebrates the world's most efficient agricultural ideas. Our peer-reviewed Best Practices Guides are just one way we help growers like you understand how to use the most resource-efficient technologies to comply with regulations and boost your bottom line.

The operational changes necessary to reduce your water footprint and minimize liquid waste discharge from your facility may be detailed, but they do not have to be a mystery. Our membership is composed of subject matter experts with the knowledge to help you to achieve water circularity in controlled environments, regardless of your crop type.

You may be looking for a source of reliable third-party information to help you conserve scarce water resources or protect our rivers and aquifers, stay ahead of future regulations, or reduce fertilizer costs for your business. Whatever the reason, we hope you lay the groundwork with the insights offered in Resource Innovation Institute's Best Practices Guides when you are considering a decision related to the systems used in your facility.

INPUT from industry leaders and partners → RESOURCE INNOVATION INSTITUTE → **EDUCATION** and advocacy about best practices for growers

Purpose

The rapidly emerging societal understanding of the finiteness of clean water and the detrimental consequences of pollution are among the greatest challenges the CEA industry faces, requiring a systems approach of conservation practices and reuse technology.

The purpose of this Water Circularity Best Practices Guide is to support you, the cultivator, and your design, construction, and operations partners in:

- Speaking the language of water circularity;
- Understanding crucial water conservation principles;
- Reviewing the available technology for treatment and recapture of multiple water streams involved in crop production;
- Maximizing incentives for energy-efficient water treatment solutions; and
- Protecting our natural water resources while aligning with your business model.

Focus

This guide will follow the principles of Reduce, Remediate and Recycle outlined by a USDA-funded Clean Water3 research initiative directed by experts at Clemson University, University of California, Oregon State University, Michigan State University, Virginia Tech, Texas A&M, University of Kentucky, University of Georgia, and University of Florida (cleanwater3.org). Any size operation will be able to implement the best practices for reducing water consumption. Advanced facilities can apply the strategies for recycling and remediating multiple water streams using physical, chemical, and biological technologies.

Scope

This guide is designed for the controlled environment agriculture (CEA) industry. CEA is defined as "the production of plants and their products, such as vegetables and flowers, inside controlled environment structures such as greenhouses, vertical farms, and growth chambers," per the University of Arizona's Controlled Environment Agriculture Center.[1] Greenhouses are defined by the International Energy Conservation Code as structures with a skylight roof ratio of 50% or more above the growing area exclusively used for the cultivation or maintenance of plants for 180 days or more.[2] Indoor farms, with or without vertical racking or towers, are a rapidly expanding division of CEA. Growth chambers and modified shipping containers, often referred to as container farms, are also included in CEA discussions. Whatever the form it takes, controlled environment agriculture is crop- and systems-agnostic.

Water circularity is defined as the designed elimination of water waste. In its most complete manifestation, water circularity may be referred to as **Minimum Liquid Discharge (MLD)**, or even **Zero Liquid Discharge (ZLD)**. MLD includes the elimination of **gray water** that is technically or economically unfeasible to remediate for irrigation, such as sanitary washdown water (used for cleaning and disinfecting), or concentrated brines from some water purification processes.

Multiple water waste streams will be discussed as targets of circularity. However, **black water**, or sewage treatment, will not be discussed, though its importance is recognized. Water used for processing, packaging, and composting will be discussed, but not the principles of those operations themselves. This guide will cover the topic of remediating and recycling nutrient solutions, but will not provide specific plant nutrient recommendations or diagnoses.

1 University of Arizona Controlled Environment Agriculture Center. (2021). Retrieved May 4, 2023, from https://ceac.arizona.edu/#:~:text=Controlled%20Environment%20Agriculture%20(CEA)%20is,vertical%20farms%2C%20and%20growth%20chambers.

2 Code change title: Horticultural Lighting cepi-185-21 summary (2022). Retrieved May 4, 2023, from https://newbuildings.org/wp-content/uploads/2022/02/IECC2024_Horticultural-Lighting.pdf

Demystify Terms

Throughout this guide, you will learn key terms related to optimizing water treatment, storage, recapture, and disinfection, and how the terms may be commonly misunderstood or misapplied. These terms will be emboldened in the text. Consult our online glossary of key CEA water terms to expand your water circularity vocabulary.

A few terms and concepts that we have chosen to use are worth delineating at the outset:[3]

- **Hydroponic Culture** will be defined as plant culture where roots grow in or are sprayed with a liquid nutrient solution.
- **Horticultural Substrate Culture** refers to plant culture that uses a solid root medium of one or more components, typically peat, coir, pine bark, wood fiber, rockwool, and/or perlite, but not containing field soil.
- **Fertigation solution** is irrigation water containing dissolved plant nutrients and is assumed in CEA to be applied at every irrigation event (except perhaps during propagation).
- **Open Systems** allow fertigation solution to drain from the crop to a waste stream after a single irrigation event.
- **Closed Systems** collect and re-use the fertigation solution multiple times.
- **Ebb-and-flood** refers to cycles of sub-irrigation followed by drainage.
- **Leachate** describes the solution that drains from a root substrate following irrigation, due to its prevalence in the scientific literature, though we recognize the industry also uses the terms “drain,” “effluent,” and “runoff.”
- **Dump water** is the hydroponic or ebb-and-flood solution that is discharged from the facility after having been used for multiple cycles.
- **HVAC** is an acronym for heating, ventilation, and air conditioning equipment. It is often referred to as **HVAC-D** when dehumidification is integrated into the unit.

CENTER IMAGE: NETAFIM.COM

[3] Caron, J. and Zheng, Y. (2021). Glossary of terms and basic characteristics to be reported in scientific publications on growing media. Acta Hortic. 1317, 55-64

How CEA Facilities Use Water

The strategies for water circularity in CEA facilities vary by the following water uses: **1)** water applied directly to plants for healthy growth, **2)** water used to regulate the plant growing environment, and **3)** process water use non-cropping related activities, such as cleaning and maintenance. Best management practices for each of these uses can reduce water consumption at any facility, large or small.

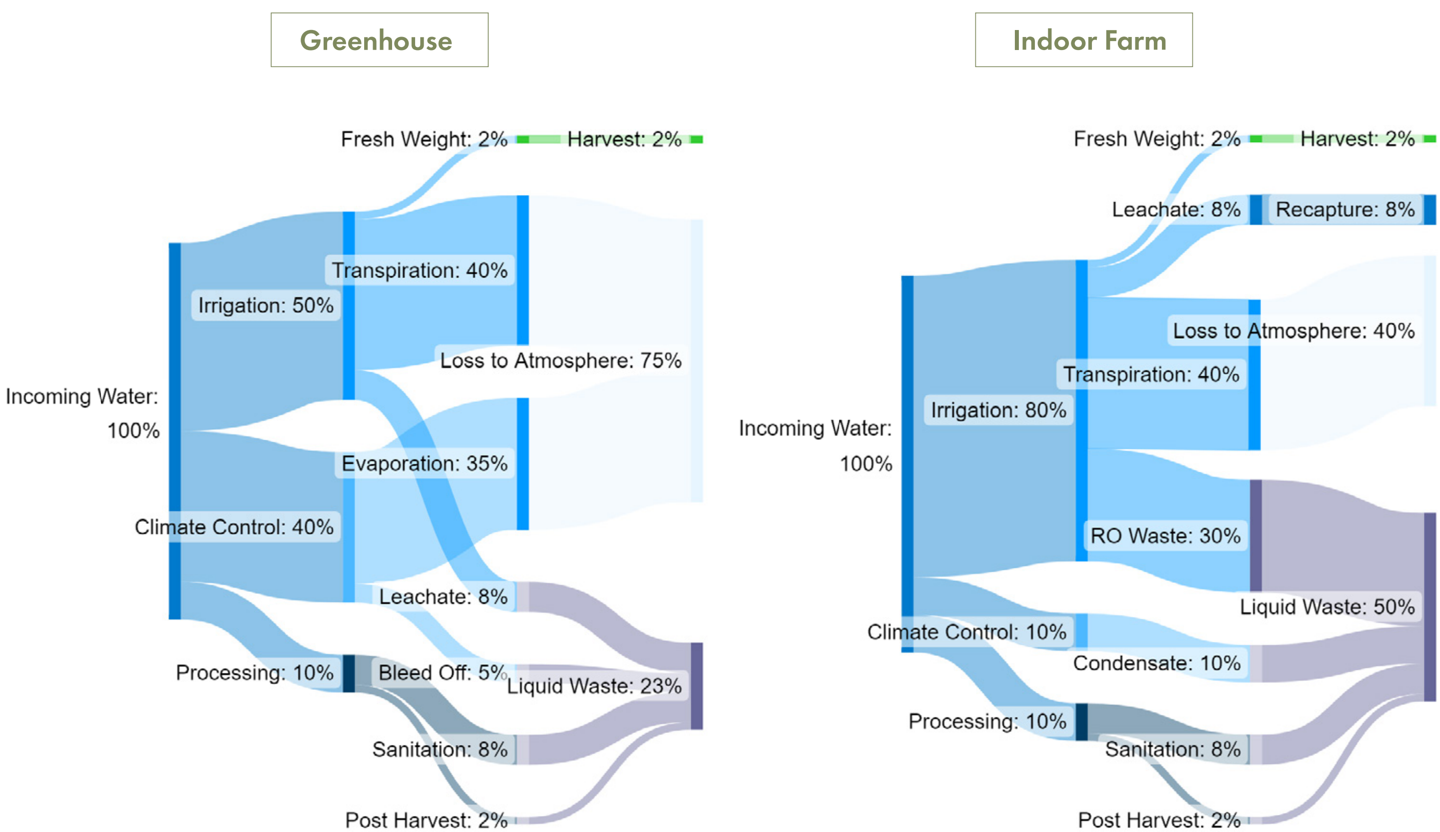
1 **Water Applied to Plants** - Water is applied to plants to avoid moisture stress and to deliver soluble fertilizers to the roots, a method known as fertigation. Foliar fertilizer, particularly solutions containing immobile elements such as calcium or iron, is often applied to the leaves in response to a nutrient deficiency. Water mist is often applied to seedlings or vegetative cuttings until root growth is established. Water is used to apply plant protection products to the foliage as a spray, aerosol, or fog, or to the roots as a drench. Ornamental plants may also have plant growth regulators applied via spray or drench. Plants may be wetted with a fine spray prior to the application of certain biological pest control products. Some operations use forceful sprays of water to remove insects mechanically.

2 **Water Used to Regulate the Plant-Growing Environment** - Heated water or steam is often used to distribute heat from a boiler to plant-growing areas. Greenhouses often are cooled with an **evaporative pad and exhaust fan system** that requires large amounts of water in the high light season that often exceeds what is needed for irrigation. Large greenhouse ranges or indoor farms may use cooling towers that operate off the same evaporative principle and create a waste stream called **blowdown water**. Humidification using purified water is performed by a fogging system or standalone fogger in large areas, and by mist nozzles or evaporative pans in growth chambers. Some facilities use water-cooled lighting to transfer heat from high-intensity discharge lamps away from the plant area. By storing it in barrels exposed to sunlight, the high thermal mass of water can be used in greenhouses to absorb heat during the day and radiate it into the greenhouse air at night. Water is also used to rinse reusable filters and filtration membranes.

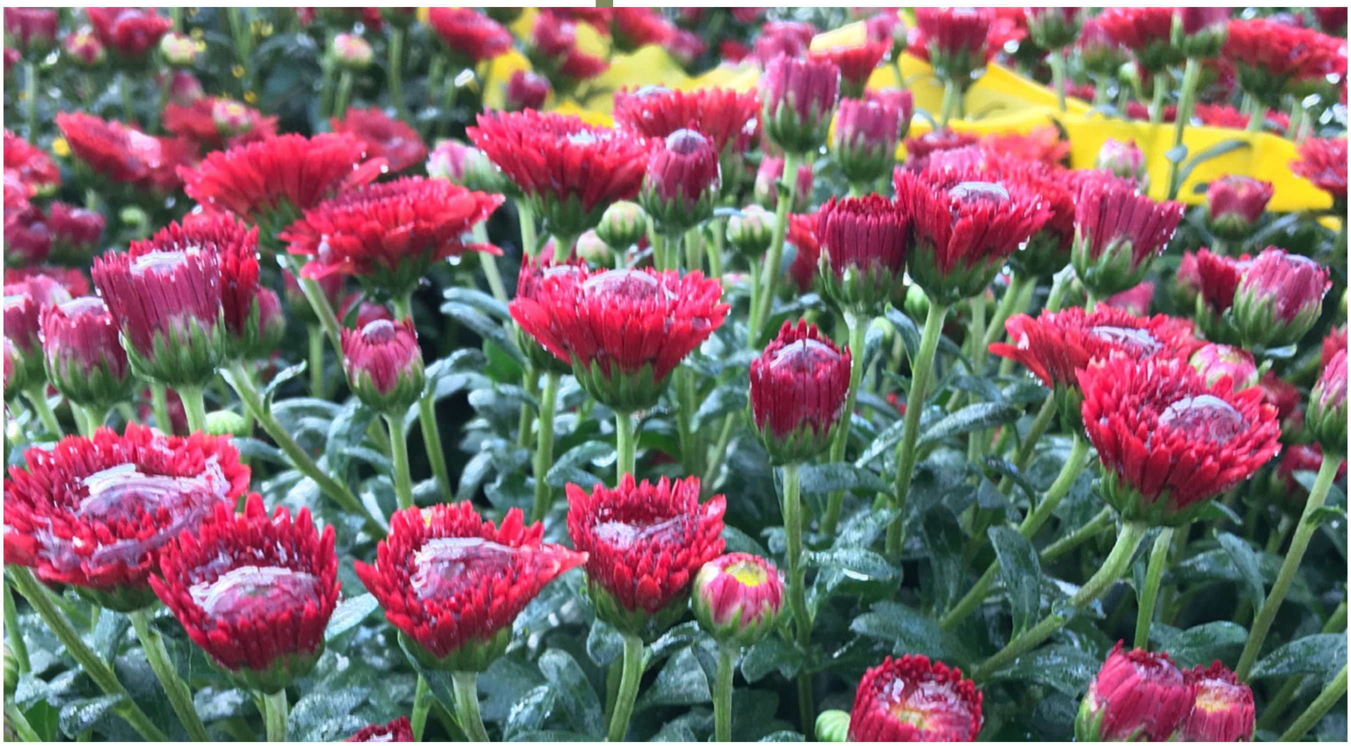
3 **Process Water Use** - Water is used in many ways to indirectly support CEA crop production or the people working in the facility. Disinfectants are applied to surfaces of plant growing areas between crops, while floors often are sanitized daily or weekly. Pots, trays, and

tools are washed in sinks or washers, while mobile tables are cleaned in designated areas. Equipment is routinely cleaned with sanitizing solutions. All of these uses are referred to as **washdown water**. Plumbing, irrigation lines, boilers, and chillers are flushed of sediment, scale, and biofilms. Personal protective equipment (PPE) such as boots and chemical-barrier gloves require rinsing and sanitizing, as well as vehicles, carts, and conveyors. Post-harvest processing and packaging activities typically require water. Water is used to clean vegetable and fruit produce and to convey it in flumes during processing. On-site composting operations require water to promote biological activity and cool the substrate.

Figure 1. The fate of incoming water in two hypothetical scenarios: 1) a greenhouse with evaporative cooling, rockwool substrate culture, standard water quality, and no water recycling and, 2) an indoor farm with HVAC-D thermal control, rockwool substrate culture, reverse osmosis purified irrigation water, and recycling of irrigation water. The greenhouse loses 98% of incoming water to either liquid waste or loss to the atmosphere, while the indoor farm loses 8% less due to recaptured irrigation water. Though not represented in the figure, the greenhouse also requires more incoming water supply because of evaporative cooling demand, as high as 100% more in arid locations.



How CEA Crops Use Water

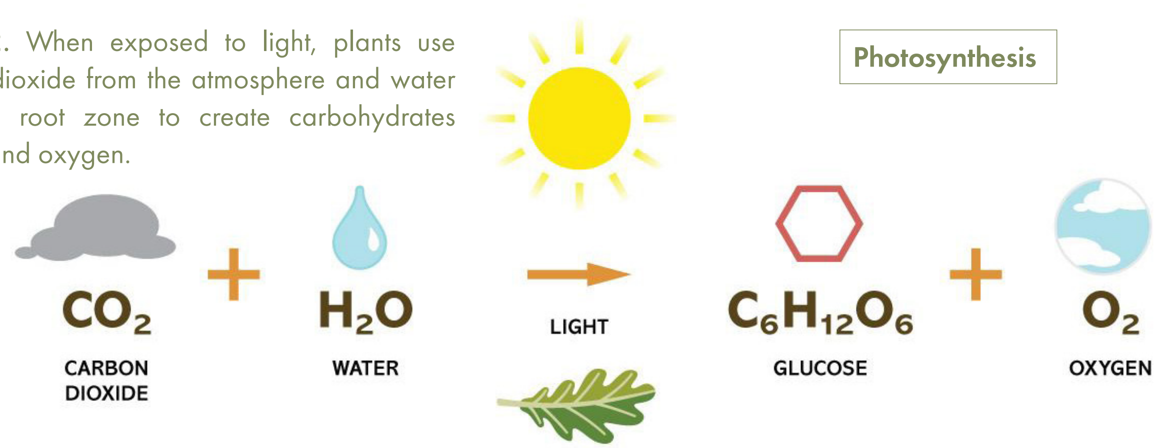


Plants provide humans with a source of nutritional elements, water, calories, and secondary metabolites linked to good health. Water is a mission-critical system in CEA facilities that must meet the needs of your crops. The needs of CEA crops are unique and affected by the cultivation approach.

Photosynthesis - Natural or artificial light empowers plants to forge sugars (glucose) using water from the root zone and carbon dioxide from the atmosphere as raw materials. These sugars can then be used as building blocks for growth and storage as well as an energy source for cellular maintenance, called respiration. Water is also used by plants to keep their leaves upright and turgid to intercept photons of light from the sun. Many herbaceous CEA crops such as lettuce and leafy greens contain 90 to 95% water by weight.

Temperature Regulation - Although photosynthesis is a critically important process for growth, only about 1% of the water taken up during the life of a plant is used by the plant

Figure 2. When exposed to light, plants use carbon dioxide from the atmosphere and water from the root zone to create carbohydrates (sugar) and oxygen.



BOTTOM MAGE: OREGON FOREST RESOURCES INSTITUTE for this process.[4] Greater than 90% is used by the plant to cool itself and transport materials from the root zone through the plant. Water evaporating from the tiny pores, or stomata, on the underside of leaves is a heat-requiring reaction, and so cools the tissue as a result.

This evaporation process is why agriculture is the most water-consumptive industry: very little water is returned to the aquifer or surface source. This water vapor will eventually produce rain or snow, but precipitation may not fall on land or in locations where it can be accessed. Practically speaking, evaporated water is lost.

Additionally, since plants are typically made up of more than 90% of water, they can regulate their temperature by leveraging water's heat-retention quality.

The Universal Solvent - A solvent is a substance in which other things can dissolve, and water is the best known general solvent. Required minerals and oxygen from the root zone are dissolved in the water taken up by plants and transported to their aerial portions. Most of the biochemical reactions required for plant processes take place in water. Even though most water is taken up and then quickly transpired out of plants, these molecules bring with them materials necessary for plant survival and are the very broth of creation.

Water Quality Required for Plant Growth

Ultimately, the quality of the water determines its use. In addition to reducing the amount of freshwater use, remediating and reusing irrigation water is one of the best ways to conserve water. The initial quality of the water source and how ions and contaminants accumulate in the solution will determine the feasibility of reusing or recirculating water.

Physical Quality of Water - Physical quality in part refers to the amount of particles and debris in the water, or **Total Suspended Solids (TSS)**, commonly measured in mg/L units or parts per million (ppm), which are equivalent units. These particles include sand, sediment, bacteria, algae, and other organic matter of size greater than 2 micrometers, whereas smaller particles are defined as **Total Dissolved Solids (TDS)**. TSS particles can clog nozzles and **drip irrigation** emitters, reduce the effectiveness of plumbing seals, increase equipment wear, and weaken other forms of water treatment. Filtration is the treatment for physical water problems.
Types of filters used for water purification include membrane filters, slow sand filters, multimedia filters, disk filters, screen filters, cartridge filters, bag filters, and paper or belt filters. Depending on the physical water quality and the CEA operation, a simple mesh screen may be all that is required, for example with a municipal or well water source. In contrast, other facilities with a pond source, for example, might require multi-staged filtration involving sequential steps.[5] A laboratory analysis can determine the size distribution of physical contaminants in your water, and purification recommendations by an irrigation or water treatment expert should be followed.

Temperature is also a physical property of water. Ideally, irrigation water temperature should be between 68-74 degrees Fahrenheit (20 to 23°C). Water pulled directly from rivers and reservoirs can be too cold to apply to plants in northern climates during winter. **Tempering** water with heat exchangers is one solution, but this requires additional energy inputs. Storing water in an indoor "**day tank**"–the volume of one day's worth of water–is a best practice for this reason (in addition to being a reserve supply in case of emergencies). Care should be taken to prevent stored water from becoming too warm by exposing the storage tank to direct sunlight. Dissolved oxygen, necessary for root growth and function in hydroponic production, decreases in water with increasing temperature.

Biological Quality of Water - Water for CEA facilities must be free of algae, viruses, bacteria, or fungi pathogenic to plants or humans. Examples of plant pathogens that can live or be distributed in irrigation water are *Fusarium*, *Pythium*, and *Phytophthora* species. Human health concerns include bacterial infections of Legionnaires' Disease, *Salmonella*, and *Listeria*. Bacteria and other microbes may also form **biofilms** inside irrigation and plumbing pipes that can lead to clogging.

Some treatments for disinfecting water are considered single-point treatments that are not effective "downstream" and are usually combined with a residual treatment. Both will be detailed later in the guide.

4 Lieth, J. & Oki, Lorence. (2008). Irrigation in Soilless Production. 10.1016/B978-044452975-6.50006-X.
5 Konjoian, Peter, et al. (2008). Water Treatment Series, Part 3: Filtration - Greenhouse Management. Greenhouse Management, https://www.greenhousemag.com/news/water-treatment-series--part-3--filtration/.

Chemical Quality of Water - Among the chemical problems that reduce water quality are high dissolved carbonates and bicarbonates (alkalinity); dissolved Ca and Mg (hardness); high **electrical conductivity (EC)** (which is a measure of TDS); high or low **pH**; concentrations of NaCl and fertilizer salts; excess nutrient ions such as iron or manganese; excess heavy metal ions such as cadmium or arsenic; and pollutant chemicals such as pesticides. River water can often be contaminated by legacy industrial factories upstream. It is imperative to have a water analysis conducted on your water source that includes heavy metals and pollutants. As with improving physical quality, a multi-stage treatment approach may be required to improve the chemical quality of water, depending on the operation.

Oxygen is necessary for roots to acquire energy for nutrient uptake through the process of respiration. Oxygen is typically available to roots via air-filled pore spaces between particles of a commercial greenhouse substrate, but in hydroponic nutrient solutions, oxygen must be replenished through **agitation** or **aeration**. Injection of some sanitizing agents such as peroxide compounds or ozone creates oxygen as a beneficial byproduct. **Dissolved oxygen (DO)** content for hydroponics should be maintained above 5 mg/L (5 ppm). Supersaturation of oxygen up to 20 to 30 mg/L can prevent low oxygen stress throughout a hydroponic irrigation system. **Source water** (surface water, groundwater, or well water) typically has adequate levels of DO, but that oxygen diffuses out of the water during storage, much like carbonated beverages go "flat."

In regions where source water cannot be treated to remove excess sodium or high EC, growers of containerized plants have found they can safely grow plants by increasing the frequency of irrigation. This practice keeps the ions from concentrating in the soil solution as a result of soil drying and leaches out accumulated ions. However, recirculating this poor-quality water concentrates the excess ions further.

Below are charts for desirable characteristics of high-quality irrigation water and special considerations for water to be used in recirculating irrigation systems. Note that sodium and chloride concentrations need to be lower when recirculating, otherwise they accumulate over time to the detriment of plant health. An online tool that can be used to interpret a water quality report for irrigation purposes is WaterQual at www.cleanwater3.org/wqi.asp.

Table 1. Desirable characteristics of high-quality irrigation water.[6]

Characteristic	Desired Level
Soluble Salts (EC)	0.0-0.5 dS/m
pH	5.4-6.8
Alkalinity (Carbonate, $CaCO_3$) (Bicarbonate, HCO_3)	40-65 ppm 40-65 ppm
Hardness ($CaCO_3$ equivalent)	<100 ppm
Sodium (Na)	<50 ppm
Chloride (Cl)	<71 ppm
Sodium Adsorption Ratio	<4

Characteristic	Desired Level
Nitrogen {N} -Nitrate (NO_3) Ammonium (NH_4)	<5 ppm <5 ppm
Phosphorus (P)	<1 ppm
Potassium (K)	<10 ppm
Calcium (Ca)	<60 ppm
Sulfates (SO_4)	<30 ppm
Magnesium (Mg)	<5 ppm
Manganese (Mn)	<1 ppm

Characteristic	Desired Level
Iron (Fe)	<1 ppm
Boron (B)	<0.3 ppm
Copper (Cu)	<0.1 ppm
Zinc (Zn)	<0.2 ppm
Aluminum (Al)	<2 ppm
Chloride (Cl)	<2 ppm
Fluoride (F)	<1 ppm

[6] Reprinted from Camberato, D., & Lopez, R. (2011). Media pH, EC & Water Quality: The Basics Of Monitoring. Greenhouse Grower. September 2001).

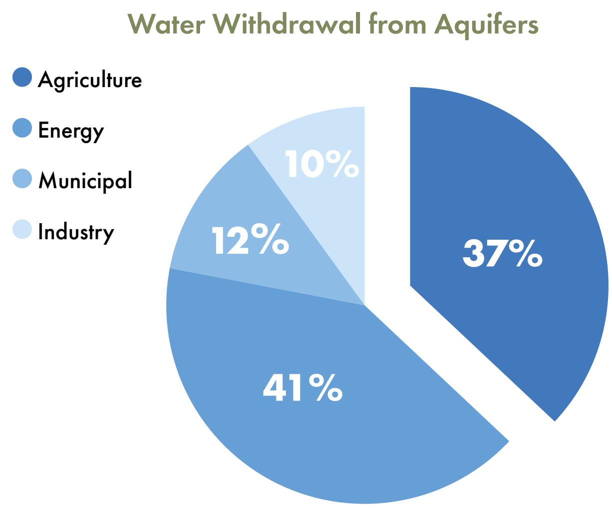
Table 2. Suitable ranges for electrical conductivity, Na concentration, and Cl concentration for hydroponics and salt-sensitive plants.[7]

Quality level	EC (mS/cm)	Na (ppm)	Cl (ppm)	Suitability for hydroponics	Suitable use
1	< 0.5	< 34	< 53	++	Suitable for all crops
2	0.5 - 1.0	34 - 57	53 - 87	+	Some discharge required in recirculating systems
3	1.0 - 1.5	57 - 92	87 - 142	±	Not suitable for salt-sensitive crops or recirculated closed systems

Current State of Agricultural Water Usage

Data is key to understanding agriculture's role in water scarcity and water pollution, and the potential of controlled environments to steward positive change. Other countries have implemented water regulations for greenhouses and indoor farms, providing examples of possible solutions.

As an industry, controlled environment agriculture needs to steward water resources. Globally, the production of plants and livestock for food, clothing, and other uses is estimated to consume 69% of the world's freshwater resources.[8] The USDA has estimated that 80% of water consumption in the U.S. is from agriculture, with rates as high as 90% in some western states.[9] Water consumption refers to water that is lost to the aquifer or surface source. For comparison, the water used by thermoelectric power facilities accounts for a higher percentage of aquifer withdrawals than agriculture, but only 3% of that water is consumptive, while the remainder is returned to surface water after treatment. Meanwhile, 80%-90% of irrigation water is lost due to the high volume of water transpired into the atmosphere by plants.[10]



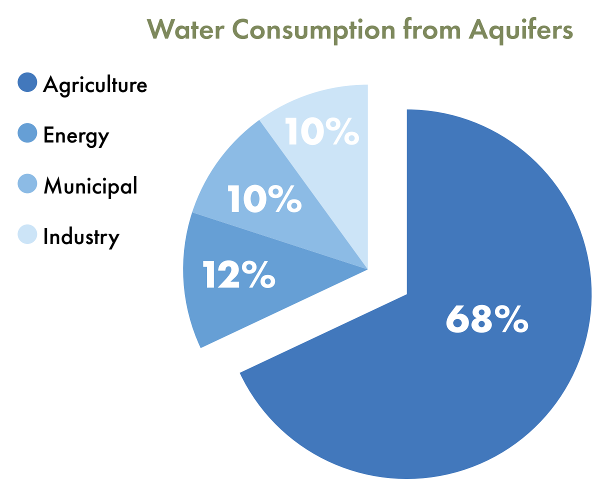


Figure 3. Water withdrawal and consumption by sector.[11]

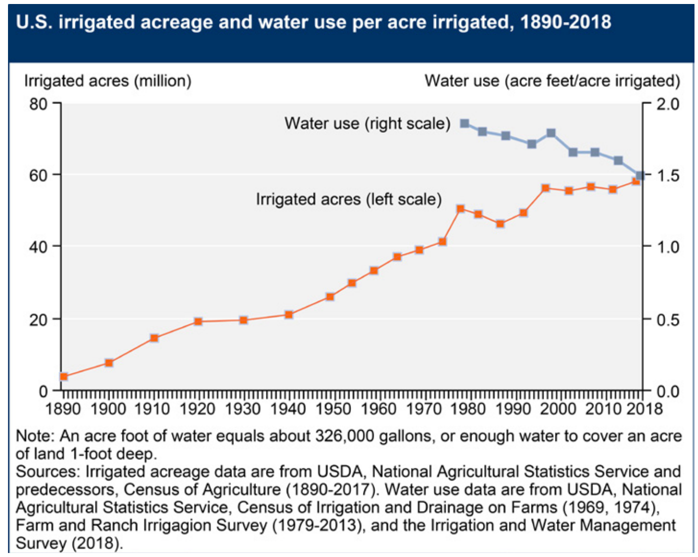
IMAGE: MODIFIED FROM U.S. GEOLOGICAL SURVEY

7 Modified from: Nutrient Solutions for Greenhouse Crops - SQM Specialty Plant Nutrition. (2020). SQM Specialty Plant Nutrition. https://sqmnutrition.com/en/book/nutrient-solutions-for-greenhouse-crops/
8 O'Neill, M., & Dobrowolski, J. P. (2011). Water and Agriculture in a Changing Climate. Hortscience, 46(2), 155–157.
9 Center for Sustainable Systems, University of Michigan. (2021). "U.S. Water Supply and Distribution Factsheet." Pub. No. CSS05-17.
10 Center for Sustainable Systems, University of Michigan. (2021).
11 U.S.G.S. Water Use. (2018). U.S. Water Use.

Controlled environment agriculture utilizes high planting densities and small root substrate volumes, requiring more frequent irrigation than traditional field production. Greenhouses have been estimated to use 22,000 gal (83kL) per acre each day for irrigation, and evaporative cooling systems may use an additional 8,000 gal/acre/day (75 kL/ha/day) during the peak cooling season.[12] In arid climates such as Arizona, evaporative cooling consumes more water than irrigation.[13] Another environmental challenge is that irrigation effluent of crops typically contains fertilizer and pest control chemicals that may pollute local ecosystems if discharged, particularly nitrogen and phosphorus known to cause algal blooms in surface waters. Eutrophication, the death of animal life from lack of oxygen, may result in cases of polluted water contaminating natural sources.

Some trends in water use statistics are favorable for the sustainability movement. The USGS survey indicates that water use for irrigation has decreased since 1980, when growers began adopting drip irrigation, indicating that new technology can reduce consumption. Cost-sharing programs that assisted growers in installing recycling systems resulted in no measurable runoff from irrigation leaving these properties. Also, growers have been willing to adopt more resilient practices. Greenhouse facilities were amenable to the adoption of sustainable practices for water conservation for at least two years following participation in educational programs, although practical strategies and education efforts may need to differ between large and small operations.[14]

Figure 4. U.S. irrigated acreage and water use per acre irrigated, 1890-2018.[15]



Regulations for protecting water resources have emerged in some regions that affect greenhouses and indoor farms. In the European Union, regulations have been put in place to eliminate nitrogen emissions from greenhouse discharge water by 2027. Since 2018, Dutch growers must treat discharge water to remove 95% of pesticides.[16] In the United States, many states are requiring water discharge permits that regulate nitrate and pesticides from irrigation and all (or part of) stormwater runoff.

IMAGE: USDA ECONOMIC RESEARCH SERVICE

12 Bailey, D. et al., (1999). Water Considerations For Container Production of Plants. www.clamerinforma.it.
13 Sabeh, N., Giacomelli, G., & Kubota, C. (2011). Water Use in a Greenhouse in a Semi-Arid Climate. Transactions of the ASABE, 54(3), 1069–1077.
14 Newman, J. (2007, September). Work with water laws. Greenhouse Management.
15 U.S.D.A. Economic Research Service. (n.d). Irrigation & Water Use. https://www.ers.usda.gov/topics/farm-practices-management/irrigation-water-use/
16 Van Der Salm, C., Voogt, W., Beerling, E., Van Ruijven, J., & Van Os, E. (2020). Minimising emissions to water bodies from NW European greenhouses; with focus on Dutch vegetable cultivation. Agricultural Water Management, 242, 106398.

Benefits, Challenges, and Priorities of Water Circularity in CEA Facilities

Water circularity offers diverse benefits for CEA facilities. In the past decade, many new technologies have been developed specifically for recapturing and remediating water for use or for rendering it safe to dispose of into the local ecosystem.

In some locations with **water scarcity**, some form of water circularity is required just to be provided a license to operate. Reduction of water waste reduces the water footprint of a facility, protecting the regional supply. Water circularity demonstrates a commitment to the surrounding community and supports a resilient supply chain.

Practicing water circularity can improve the competitive advantage of CEA. Recirculating irrigation water has been shown to reduce water consumption by 20%-40% and fertilizer costs by 40%-50%.[17] Growers leveraging water recirculation systems have reported a return on investment in as little as two years from fertilizer cost savings alone.[18] A detailed study of actual costs from eleven ornamental plant growers in 2016 found that water sanitation cost $0.07–$1.00 per 1,000 gallons, while water-soluble fertilizers added $3.80.[19] In 2022, Rutgers University developed an online tool for estimating return on investment for water recycling in nurseries that may apply to controlled environments.[20]

Consumer attitudes also can be influenced by knowing a product's real water cost.[21] This is especially true given the media's focus on water scarcity in the western U.S. However, care must be taken that promotional messaging does not overstate benefits, often referred to as greenwashing.

17 Mohammed, N. (2019). The Advantages of a Closed Hydroponic System in Commercial Greenhouses [Slide show; Powerpoint]. Government of Alberta. https://www1.agric.gov.ab.ca/$Department/deptdocs.nsf/all/green14458/$FILE/Nabeel%20J%20M-%20Oct%202017.pdf

18 Zylstra, A. (2021). Water Recycling and Sanitation. In Ball Redbook: Greenhouse Structures, Equipment and Technology (19th ed., Vol. 1, pp. 93–101). Ball Publishing.

19 Raudales, R. E., Fisher, P. B., & Hall, C. B. (2017). The cost of irrigation sources and water treatment in greenhouse production. Irrigation Science, 35(1), 43–54.

20 Gottlieb, P. D., Brumfield, R. G., Cabrera, R. I., Farnsworth, D., & Marxen, L. J. (2022). An Online Tool for Estimating Return-on-investment for Water Recycling at Nurseries. Horttechnology, 32(1), 47–56.

21 Hoekstra, A.Y., Chapagain, A.K., Aldaya, M.M. and Mekonnen, M.M. (2011). The Water Footprint Assessment Manual: Setting the Global Standard. Earthscan, Washington DC, London.

Challenges to adding water recirculation technologies include a high cost of implementation. Coupled with the low cost of water in some regions, this creates an economic disincentive. Also, the disparity in water scarcity between regions has resulted in great differences in regulation by states and local municipalities. Without innovative solutions and benchmarking of water circularity, investors are unable to analyze a company's environmental, social, and governance (ESG) success. Another challenge is growers' hesitation to adopt water circulation practices due to food safety concerns, the possibility of disease spread, or distrust of water treatment suppliers or technologies. This guide can be very helpful in addressing these concerns by providing an unbiased knowledge transfer on what is available, how it can be applied, and the questions growers should be asking of their potential suppliers.

The table below sets out a priority ranking for different types of water waste based on the positive environmental or operational impact that would arise from either reducing this source of waste, or from capturing, treating, and reusing this waste as a resource. The weighting leans heavily toward the types of water that are used in all CEA facility types and the volume of waste they represent. This focus has an industry-wide impact and addresses "low-hanging fruit" to hasten positive outcomes.

Table 3. Priority ranking and attributes of water waste types.

Priority Rank	Type of Water Waste	Relevant To All Facilities	Potential High Waste Volume	Release Causes Environmental Harm	Potential Crop Damage	Substitute for RO Water	Potential to Improve ROI on Treatment Costs	Difficult to Remediate
1	Over Irrigation and Leaks	X	X	X	X		X	
2	Irrigation Leachate	X	X	X			X	
3	Pesticide Drench/ Overspray	X		X				X
4	RO Reject Water		X					X
5	Evaporative Cooling Pad Bleed-Off		X					X
6	Condensate		X			X		
7	Washdown Water	X						X
8	Blowdown Water							X

SECTION 01

Reducing Irrigation Water Use in Hydroponic Culture

A 2021 academic study on vegetable crops reported hydroponic systems were more water efficient than drip-irrigation applied to pots of compost-based substrate, while also capable of producing higher quality produce.[22] Hydroponics, especially in controlled environments, has the potential to improve crop water efficiency (the number of liters of water per kg of produce). However, inefficiencies occur in hydroponics when there is excessive discharge of nutrient solution. Hydroponic technology provides a remarkable potential to reduce water consumption, though capital expense, a steep learning curve, and crop risk pose challenges. This section details the unique attributes of different hydroponic systems.

SECTION 1 CONTENTS:

> Nutrient Film Technique (NFT) systems

> Vertical Nutrient Film Technique (VNFT)

> Deep Flow Technique (DFT)

> Raft Culture

> Aeroponics

22 Verdoliva, S. G., Gwyn-Jones, D., Detheridge, A. P., & Robson, P. (2021). Controlled comparisons between soil and hydroponic systems reveal increased water use efficiency and higher lycopene and -carotene contents in hydroponically grown tomatoes. Scientia Horticulturae, 279.

Growers considering changing their plant culture to reduce the consumption of water, fertilizer, and plastic pots and trays should understand that hydroponic systems require more attention than horticultural substrate culture. Without a root substrate to buffer pH and temperature, hold nutrients, and provide pores for air exchange, these variables need to be constantly monitored and adjusted by the grower. Managing these risks involves monitoring and adjusting solutions daily, either manually or via automated systems. Water-borne plant pathogens can spread very quickly once an infection starts in a hydroponic system.

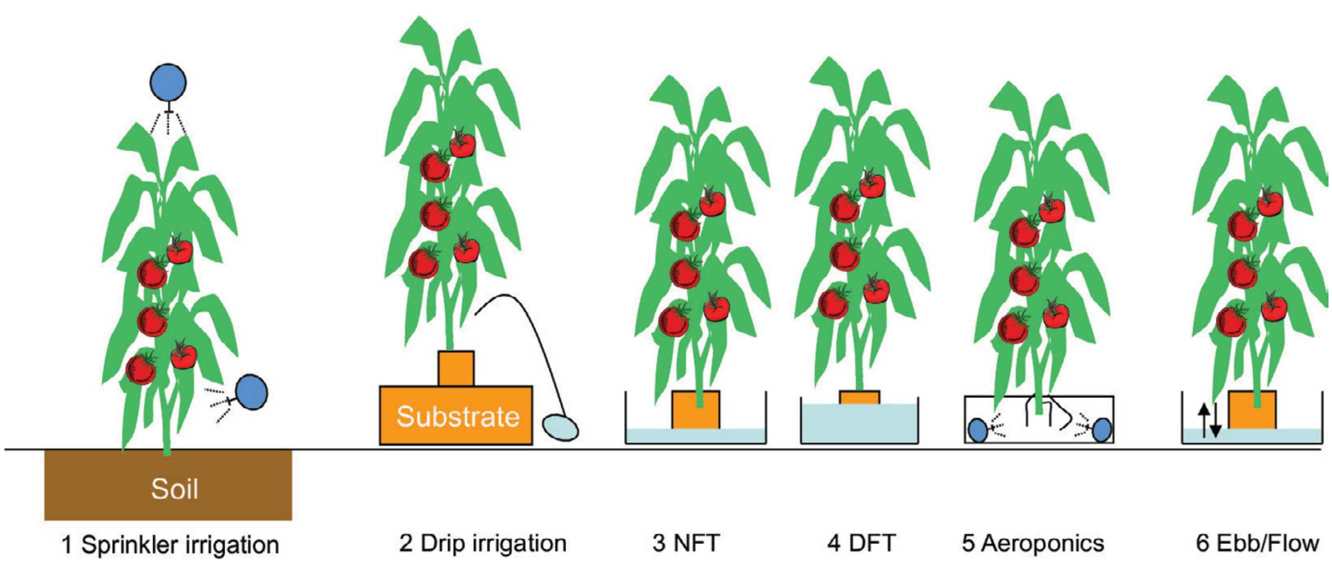
Though the definition varies by source, this guide will refer to hydroponics as systems where plant roots grow in liquid or a liquid spray. A common practice with hydroponic systems is to reuse the nutrient solution for 5-10 days while "topping off" as needed by adding water and concentrated nutrient solution, usually to maintain a target EC and pH with an automated dosing system. Some growers will dump the entire solution due to nutrient imbalances and the accumulation of excess ions of either nutrients or contaminants such as sodium.

(In the next section, we will examine water reduction in horticultural substrate culture, where roots grow in a solid substrate such as commercial soilless mixes, rockwool, and coco coir.)

Nutrient Film Technique (NFT) systems create a constant flow of nutrient solution down the gentle slope of a closed gutter, forming a nutrient film with which roots are in contact. Plants are suspended through holes in the gutter. Any nutrient solution that is not absorbed by roots drains by gravity to a reservoir and is recirculated with a pump. Oxygen is added to the solution either with a bubbler or by the agitation that occurs during the draining back to the reservoir. NFT is the most common system for CEA production of lettuce and leafy greens. Cultivating large plants using NFT is a challenge due to large root masses and the toppling of shoots.

Figure 6. Standalone system of NFT gutters and reservoir (left) and planted gutters.

Figure 5. Conceptual diagram of different hydroponic systems.[23]



[23] Reprinted from Soilless Culture, Second Edition, E.A. van Os,Th. H. Gieling,J. Heinrich Lieth. (2019). Chapter 13: Technical Equipment in Soilless Production Systemsl, pp. 587-635, with permission from Elsevier.

Vertical Nutrient Film Technique (VNFT) - As the name implies, this technique uses the same principles as NFT except with a vertical gutter or tower. Some systems incorporate capillary cloth that the roots penetrate, making this a hybrid of hydroponics and horticultural substrate culture. Other vertical systems install spray nozzles in the gutter, making them a hybrid of VNFT and aeroponics.

Remarkable production efficiencies (measured in harvested material per floor area unit) can be achieved with vertical systems, and some of the largest indoor farms in the world with gutters up to 10 meters tall utilize this technology. Disadvantages to both NFT and VNFT production are the energy required for pumps, potential swings in solution pH, and the quick onset of stress if the nutrient flow is interrupted.

Figure 7. Vertical NFT systems.

IMAGE LEFT: EDEN GREEN TECHNOLOGIES [LEFT] AND FARMBOX

Deep Flow Technique (DFT) - In this system, also called Deep Water Culture (DWC), plant roots are completely submerged in an aerated nutrient solution as opposed to a thin nutrient film. This larger volume of water provides a buffer against pH fluctuations and reduces the risk of water stress from a malfunctioning pump. Many variations of DFT containers exist, including PVC pipes, rows of interconnected pails, or deep trays. In PVC and pail systems, the nutrient solution is continuously circulated by pumps from a reservoir where adjustments to pH and EC can be more easily made. Deep tray systems may not have an attached reservoir, but the volume can be "topped off" with fresh diluted solution as needed. In all systems, seedlings are first propagated, then seated into pre-drilled holes of the container systems when roots emerge.

Figure 8. DFT system.

Raft Culture - Raft culture is a scaled version of DFT described above, using expanded polystyrene (styrofoam) plant trays, or "rafts," that float on the surface of a deep tray or indoor "pond," allowing the roots to grow into the aerated nutrient solution. The rafts may have planting holes at regular spacing, or thin slits for root penetration. With slitted rafts, leafy green or herb plants can be sown directly in a small volume of water-absorbent vermiculite or perlite, eliminating the transplanting step. Massive hydroponic greenhouses utilize raft culture, using permanent ponds with concrete walls to contain the solution rather than deep trays supported by tables. In some cases, newly seeded rafts are placed on one end of the pond while rafts are harvested on the other end, with the rows of rafts moving like train cars from one end to the other over a period of about three weeks.

One of the primary disadvantages of DFT techniques is a large amount of wastewater created if the nutrient solution is routinely discarded after several days of recirculation.

Figure 9. Raft culture on a pond with floating polystyrene trays.

Aeroponics - Aeroponics operates by a completely different irrigation system where the nutrient solution is pressurized and forced through nozzles to create a spray mist that is applied every few minutes. This has been shown to greatly increase the root mass of crops, which can translate into 7%-50% higher yields than field-grown crops like basil, chard, red kale, and parsley.[24] Oxygen is more readily available to roots than other systems. Another advantage of this system is decreased water waste, as it uses less water than NFT or DFT. Due to their much lighter weight, aeroponic units are suitable for vertical production as horizontal trays stacked one on top of the other, with thin LED light bars above each layer of plants. Recently, a new technique of propagating stem cuttings using an aeroponic "submist" applied within an enclosed rooting chamber improved rooting in several species while reducing water usage by 67%.[25] Disadvantages of aeroponics include even greater crop risk than NFT during pump failures, power outages, or clogged spray nozzles. Pump energy requirements can be another potential disadvantage to operations looking to reduce their electric load.

24 Suman Chandra, et al., (2019). Assessment of Total Phenolic and Flavonoid Content, Antioxidant Properties, and Yield of Aeroponically and Conventionally Grown Leafy Vegetables and Fruit Crops: A Comparative Study. Evidence-Based Complementary and Alternative Medicine, vol. 2014.

25 Burnett, S. E., & Peterson, B. J. (2022). Propagation of Herbaceous and Woody Perennials in Submist and Overhead Mist Systems. Journal of Environmental Horticulture, 40(4), 164–169. https://doi.org/10.24266/2573-5586-40.4.164

Reducing Irrigation Water Use in Horticultural Substrate Culture

Production in container substrates can also be very water and nutrient efficient. However, inefficiencies from water and nutrient discharge, in addition to plant diseases, occur when excess irrigation is applied to the substrate beyond plant needs. Any facility can conserve water through best management practices, no matter its level of technology. Though much of this guide will be dedicated to water remediation equipment and operation, just as important are the everyday decisions of growers and the often thankless tasks of preventative maintenance that reduce water waste. New technologies are emerging to assist the grower in making more accurate irrigation decisions to reduce waste.

Benchmarking and Comparison - Of primary importance is benchmarking water use, following the adage, "You can't manage what you don't measure."

SECTION 2 CONTENTS:

> Benchmarking and Comparison
> Developing a Culture of Water Conservation
> Impact of Cultivation Environment on Irrigation
> Impact of Cultural Practices on Irrigation
> Selection of Irrigation Systems and Equipment or Horticultural Substrate Culture
> Managing Leach Fraction to Reduce Waste
> Reducing Irrigation Waste with Smart Controls

Best practices in the design of CEA facilities include installing **in-line flow meters** to monitor water usage and troubleshooting equipment problems before they result in plant stress. Ideally, multiple flow meters are installed to monitor irrigation separately from other building processes, and possibly within different cultivation areas to accurately measure the effectiveness of water conservation efforts. These flow meters should interface with the irrigation controller or the climate control system of the cultivation area for logging and alarming. **Ultrasonic flow meters** are expensive but portable; they attach to the outside of the pipe and can be removed and relocated. A combination of in-line and ultrasonic flow meters provides practical and flexible capability. Best practices also include **variable-speed irrigation pumps** for energy reduction.

When possible, compare irrigation metrics against published research or industry reports. Daily water requirements by crop type are described in the table below. Greenhouse crops in containers of commercial soilless mix range from 0.25 gallons to 1.5 gallons/ft^2/day (roughly 10 liters to 61 liters/m^2/day).[26]

Table 4. Product water use for 1kg of fresh tomatoes grown in various climates[27]

Production Method	Country	Product water use (L/kg)	Product water use (gal/lb)
Open field, general	Israel, Spain, Turkey	100-300	12-36
Open field, drip irrigation	Israel	60	7
Greenhouse, unheated plastic	Spain	40	5
Glasshouse, unheated	Israel	30	4
Greenhouse, regulated ventilation, plastic	Spain	27	3
Glasshouse, advanced controls, CO_2	Netherlands	22	3
Glasshouse, advanced controls, CO_2, closed hydroponic system	Netherlands	15	2
Closed Greenhouse, advanced controls, CO_2, closed hydroponic system	Netherlands	4	0.5
Greenhouse, evaporative cooling	Mexico	Estimated: 100	Estimated: 12

[26] Aldrich, R. A., & Bartok, J. W. (1994). Greenhouse Engineering. Natural Resources.
[27] Modified from Nederhoff, Elly & Stanghellini, Cecilia. (2010). Water use efficiency of tomatoes - in greenhouses and hydroponics. Practical Hydroponics & Greenhouses 2010 (2010) 115.

For a more finely-tuned example, the table below shows irrigation frequency increases while volume per irrigation decreases as the light energy to the crop increases.

Table 5. Irrigation frequency and volume as a function of light radiation for drip-irrigated tomatoes growing in rockwool substrate.[28]

Light Radiation (μmol/m²/s)	Frequency/hour	Volume (ml)/Irrigation
400	0.5	135
800	1.1	128
1200	1.9	113
1600	3.0	98
2000	4.1	84

In another example, a study on cucumbers grown in rockwool with drip irrigation reported that by increasing nutrient solution strength, the leach fraction could be reduced from 29% to 17% without impacting yield.[29] However, water contaminants (such as sodium in irrigation source water) can limit the ability of growers to reduce the leaching fraction. Comparing a facility's water use to these published reports could inform the design of trials growers might conduct under their conditions to maximize water reduction.

Key Performance Indicators (KPIs) for water efficiency in CEA facilities as defined by Resource Innovation Institute.

Facility Water Efficiency
Efficiency of annual water use in units of gallons/sq ft of canopy. A lower value is better; a higher value is worse.

= Total Gallons / Square Feet of Canopy (gallons/sq ft)

Crop-Specific Water Productivity
Efficiency of annual gallons of water use per production. A lower value is better; a higher value is worse.

= Total Gallons / Total Production (gallons/lb)

Developing a Culture of Water Conservation - Instilling employees with a conservation ethic by sharing data on facility water usage and key performance indicators (KPIs) and rewarding improvements can reduce water and fertilizer consumption. Start simple: A nozzle or hose leaking one drop per second will waste 113 gallons per month.[30] Employees who are recognized for their conservation ethic will be more likely to repair these leaks and malfunctions and turn off irrigation for areas that no longer require it.

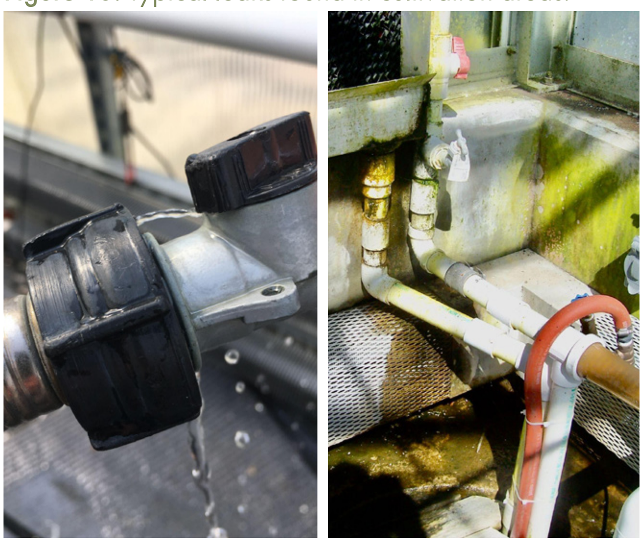
Employees making irrigation decisions may be less likely to overwater if trained and acknowledged for proper work. A common problem for facilities that rely on team member decision-making is the tendency to "water and forget it," especially on weekend shifts, rather than closely evaluate crop needs. For this reason, automating water systems can improve water efficiency. However, without close manual observation, automated systems can fail. In the worst case, an electronic valve doesn't close as programmed due to failure, flooding your crops and wasting water and nutrient resources.

In most circumstances, overwatering in container production is a result of watering too frequently rather than applying too much volume in a single irrigation. Different substrates have different water-holding capacities, and this is further influenced by the dimensions of the container it fills. Due to gravity's pull, a tall container will hold less water than a short,

[28] Lee, A., Enthoven, N., & Kaarsemaker, R. (2016). Best Practice Guidelines for Greenhouse Water Management. GRODAN and Priva.
[29] Xiong, J., Tian, Y., Wang, J., Liu, W., & Chen, Q. (2017). Comparison of Coconut Coir, Rockwool, and Peat Cultivations for Tomato Production: Nutrient Balance, Plant Growth and Fruit Quality. *Frontiers in Plant Science, 8.*
[30] Bartok, Jr., J. W. (2022, June). Tips to conserve water. Greenhouse Management.

squat container, even if their substrate volumes are the same. The tall container is said to have less **container capacity**, beyond which any more water that is applied leaches out from the bottom of the container. Short, squat containers will stay wet longer, making them less likely to cause water stress but more likely to be overwatered. Overwatering impacts plant health by reducing oxygen, as the pores of the root substrate fill with water and air is pushed out. Lack of oxygen, or **hypoxia**, reduces the respiration process in roots. Respiration is required for energy production for cell maintenance and growth. Prolonged hypoxia creates an anaerobic environment that is conducive to root diseases caused by *Pythium* and *Rhizoctonia*.

Figure 10. Typical leaks found in cultivation areas.



Impact of Cultivation Environment on Irrigation - Providing optimum climate conditions for the crop can reduce time-to-harvest, which results in water savings because of the shorter crop duration. Best management practices for conservation also include a thorough understanding of how the environment surrounding the crop impacts water usage.

Vapor pressure is the concentration of water molecules evaporated in the air, with more water molecules generally meaning more vapor pressure. Just inside the stomata, the air is at or near saturation, creating a very high vapor pressure. The surrounding air is often less than saturated, creating a lower pressure. Transpiration is driven by this **vapor pressure deficit (VPD)**, with water evaporating from stomata into the surrounding air as these opposing pressures seek equilibrium. When water evaporates from the stomatal pore, more water is drawn up the plant due to the cohesion of water molecules, like links of a chain. The greater the difference between the vapor pressure of the stomata and the surrounding air, the higher the VPD, and the more water is taken up by the roots. Since this is a pressure measurement, the units of VPD are most often reported in kilopascals (kPa) of pressure. Typical ranges for optimum VPD are 0.8-1.5 kPa, depending on the species, cultivar, and stage of growth.

How can an understanding of VPD and environmental interactions with crops help a grower conserve water? Growers can adjust temperature and relative humidity to maintain optimum VPD, using their climate control systems. A new generation of growers has come to realize that temperature recommendations are no longer set in stone, especially if relative humidity cannot be effectively controlled due to weather or lack of dehumidification equipment. Adjusting temperature according to relative humidity to ensure an optimum VPD is often a better strategy for plant health and water management. Maintaining a VPD below optimum means water and nutrients are not being drawn into the plant to optimize growth, reducing water usage but at the cost of yield and quality. *Too high of a VPD can result in more water being consumed than necessary* while also potentially reducing yield and quality due to closed stomata, reduced photosynthesis, wilting, and heat stress when the plant evapotranspires water more quickly than it can replace through water absorption by roots.

Making sure climate sensors are functioning properly and calibrated is a best practice for reducing water consumption by ensuring accurate VPD monitoring. For example, sensors are typically in an enclosure protected from direct light that would otherwise heat the sensors. The enclosure has an aspirating fan drawing in fresh air. This fan, typically the same size as a computer fan, can fail without any indication, resulting in the air inside heating above the ambient conditions, which in turn affects the VPD reading and other climate control systems. Standard operating procedures (SOPs) should be developed for routine fan inspections of fans and sensor calibrations.

Other climate variables impact irrigation. Having a growing area full of plants is desirable, as plants both cool the room and transpire water. The air inside a half-empty room of plants may be hotter and drier, requiring more irrigation. Lighting and shading also impact water usage.

For example, greenhouse shade curtains drawn closed on bright sunny days can keep the leaves and the surrounding air cooler, thereby reducing water irrigation and the need for evaporative cooling systems (if used).

Impact of Cultural Practices on Irrigation - Cultivation decisions such as container size, the water holding capacity of the root substrate, the plant species, and even cultivar selection can also impact water usage.

Open irrigation systems that drain to waste after each irrigation should consider substrate ingredients that increase water-holding capacity while choosing a pot that will assure drainage for proper air exchange.

Many growers have a preferred horticultural substrate and base their irrigation decisions around that. In contrast, given the ever-increasing importance of reducing water waste, it may make more sense to choose an irrigation and fertilization strategy first, and then plan the other components of the cultivation system around that. This provides more potential for water savings, as irrigation practices won't be dictated by the other variables. Likewise, the chosen cultivation system will have a great impact on water use and waste.

In many facilities, multiple fertilizer recipes are delivered to the plant-growing areas. Delivering a new formulation through the same plumbing creates the need to purge out the old solution, resulting in fertilizer solution going directly to waste without having been used by plants. Alternatively, filling storage tanks with each recipe and delivering the nutrient mixes through dedicated pipes can eliminate the need for this flushing, though at a greater cost for plumbing, tanks, and pumps.

Other practices to consider include grouping crops with similar irrigation needs in the same irrigation block, choosing cultivars that have shown more resilience to water stress, and culling unhealthy plants (instead of trying to salvage them).

Selection of Irrigation Systems and Equipment for Horticultural Substrate Culture - Careful selection of systems and equipment can reduce irrigation water waste. As much as half the water applied by a hose without a shut-off at the nozzle end doesn't make it into a pot, wetting the floors and aisles instead. Well-designed **spray booms** with overlapping nozzle patterns that travel across the canopy are also highly efficient for short crops with a closed canopy. Nozzles for booms or other overhead sprinkler heads that create spray droplets that penetrate the foliage and reduce drift should be selected. Spray patterns of nozzles should have double or triple overlaps and routine maintenance SOPs for nozzles should be carried out to ensure uniform coverage. For testing uniformity and volume applied, growers can place dishes or beakers at multiple places on growing tables and measure output.[31]

- **Ebb-and-flood systems** can be used on pots of all sizes, though the column height and physical properties of the substrate need to be considered. Tables are filled with nutrient solution periodically, and gravity drains the solution back to the reservoir through a table drain and associated plumbing. Typically, only 5-10 minutes is required during the flood stage, with 30 minutes being the maximum. Closed systems such as ebb-and-flood tables (and hydroponics) have been shown to save up to 40% of irrigation water and between 35% and 54% of nutrients.[32] **Flood floors** operate by the same principle as ebb-and-flood tables, just at a larger scale, with massive reservoirs located below the floors. A challenge of using these systems is maintaining level tables and ensuring a 0.5% slope to drain tables and floors.

Figure 11. Ebb and flood tables filling from the supply line, bottom left.

IMAGE: NETAFIM

31 Irrigation System Testing. (n.d.). Understanding Crop Irrigation. Retrieved May 9, 2023, from https://fyi.extension.wisc.edu/cropirrigation/irrigation-system-testing/
32 Nikolaou, G., Neocleous, D., Katsoulas, N., & Kittas, C. (2019). Irrigation of Greenhouse Crops. Horticulturae 2019, 5, 7.

Figure 12. Flood floor (left) and boom irrigation sprayer.

- **Drip irrigation,** even without remediation and reuse of water, is dramatically effective at reducing the water consumption of crop production. Since its implementation in outdoor agriculture in the 1980s, water consumption by U.S. agriculture has dropped significantly despite the acreage under production increasing, due in part to drip irrigation of fruit and vegetable crops.[33] Since its introduction into the nursery and greenhouse industry in the 1960s, drip irrigation has become the most common approach in horticultural substrate culture. It reduces waste by applying water directly to the substrate at a slow rate which allows for improved absorption and less drainage.

> Best practices for drip irrigation systems include choosing emitters with the appropriate flow rate. For example, for production in rockwool slabs, tomatoes and cucumbers typically have emitters with a flow rate of 3 liters/hour (0.8 gal/hour), while peppers would use 2 liters/hour (0.5 gal/hour) due to their higher planting density. Manufacturers of drip irrigation components can provide recommendations. Typically, two emitters are used per pot or one per plant in a slab. The drainage slit made in a rockwool slab should be made at least 20 cm away from the nearest dripper, and typically only one slit is needed if the slab is on a level surface.

- **Pressure-compensated drip emitters** reduce waste by ensuring all drippers stop and start emitting at the same time. Otherwise, longer irrigation duration is required to uniformly wet the plants at the distant end of the dripper line, while closer plants receive excess water. Drip systems should be built with flush valves on the main, sub-main, and lateral lines to periodically flush sediment that can clog emitters. Where irrigation leachate is not recaptured, drip lines may be divided with manual shut-off valves to create two or more sections. For crops that are not harvested simultaneously, this will prevent orphaned drippers from wasting water. Some drip systems come with shut-offs for individual emitters so that water can be shut off for a single plant culled.

Proper drip system maintenance will ensure effective operations while minimizing water waste. Inspecting crops during irrigation cycles can help identify faulty drippers, which can be flagged for replacement or repair. Drippers should be routinely tested for uniform output. Placing a dripper in a dish or beaker in multiple locations along a drip system is one way of testing uniformity. A discrepancy of greater than 7%-10% indicates the emitters should be either cleaned or replaced.

Figure 13. Drip emitters (left) and drip tape system.

IMAGES BOTTOM: GALEMA'S GREENHOUSE

33 U.S.D.A. Economic Research Service. (n.d).

- **Drip tape systems** are used more often in outdoor plant nurseries than in indoor farms or greenhouses. Flexible polyethylene tubing with pre-punched holes is stretched over a row of closely spaced pots. When pressurized, water dribbles from the holes to slowly saturate the root substrate. The advantages of this system are its lower supply and installation costs and the ease of checking operation with a quick visual scan. Disadvantages include a lack of pressure regulation and accuracy, as well as more risk: A slip, kink, or tear of the drip tape can result in poor irrigation for every pot downstream.

- **Trough culture** is frequently used for CEA crops in horticultural substrate culture, particularly strawberry production. Plants in pots are grown in suspended gutters or troughs and nutrient solution is allowed to stream down the trough's slope rather than having to fill it, similar to NFT. The substrate absorbs the solution via capillary action during intermittent irrigations. The gaps between the troughs improve air circulation relative to crops on solid-bottom tables.

Managing Leach Fraction to Reduce Waste - Horticultural substrate culture systems typically require an excess of 10%-20% water volume above the container capacity in order to keep fertilizer salts from accumulating in the soil and to bring all plant units to container capacity during an irrigation event in cases where the irrigation system is not uniform. Excess salts in growing media reduce water uptake and may damage the roots. This excess water is referred to as **leachate**, and the percent leachate of the total volume applied is the **leach fraction**. If not recaptured, remediated, and reused, leachate becomes waste that can cause eutrophication of waterways due to its N and P content if released into the environment. Therefore, best practices should include monitoring and managing this leachate to maintain a 10%-20% leach fraction.

Leach fraction will need to be monitored during the varying stages of plant development. For example, crops in the reproductive stage often have lower water uptake compared to the vegetative stage, so without adjusting the cycle duration, more potential waste is produced.

Crops that are sub-irrigated by ebb-and-flood or trough culture systems do not create leachate, as plants will not absorb more than their container capacity. That does not mean they are without a waste stream. If not carefully managed, fertilizer salts will accumulate in the substrate, requiring routine "flush" or "leach" irrigations with excessive clear water to reduce the build-up, and this excess is often discarded into the environment. Also, as described earlier, recaptured and reused irrigation ebb-and-flood solutions are often discarded after a certain number of cycles, creating waste.

Reducing Irrigation Waste with Smart Controls - No matter what kind of culture system is used, automation with irrigation controls–whether standalone or integrated into the climate control system–is one of the most powerful tools a grower can wield for steering crops and reducing water waste. Substrate systems can benefit from using multiple environmental variables to determine the frequency and duration of irrigation cycles, while the management of hydroponic systems can be greatly simplified by automated recirculated nutrient solution pH and electrical conductivity (EC) adjustments.

- **Timeclock automation** of watering based solely on time (for example, one cycle every 6 hours) may save labor but typically results in more water waste. Particularly in a greenhouse environment with variable lighting, a grower is likely to program the timeclock for the worst-case scenario to avoid water stress during bright light hours. This approach results in too frequent watering in darker periods. In a study using nursery crops, timeclock irrigation *increased water use by 20% to 40% and nutrient emissions by 39% to 74%* compared with irrigation based on environmental models.[34] Variable lighting is not an issue in an indoor farm, but the programming would still need adjustments according to plant size and growth stage.

- **Period timeclock automation** typically involves dividing the 24-hour cycle into periods, with each period having a specific irrigation interval and duration. For example, most crops are not watered during the dark period, or even within hours before darkness, in order to avoid excessive relative

[34] Nikolaou, G., Neocleous, D., Katsoulas, N., & Kittas, C. (2019). Irrigation of Greenhouse Crops. Horticulturae 2019, 5, 7.

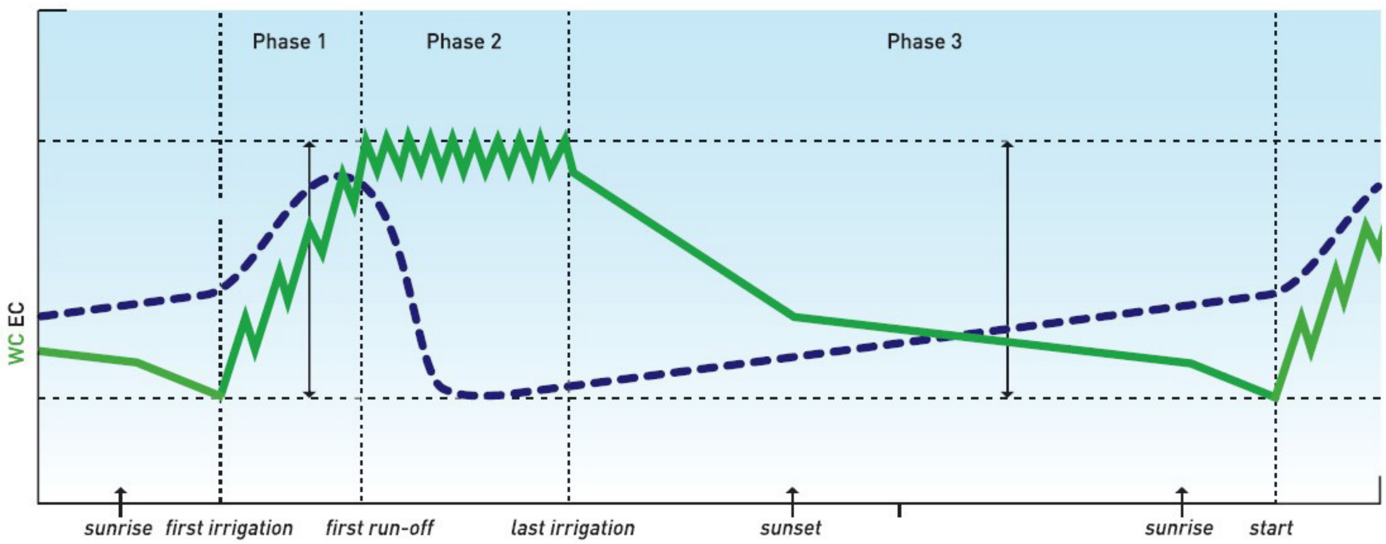


Figure 14. Water content (green solid line) and EC (blue dashed line) of rockwool over the course of one day in a greenhouse.

humidity levels conducive to the germination of fungal disease spores. As seen in the figure above, irrigation of vine tomatoes in a greenhouse was within a window of 1-2 hours after sunrise and 1-2 hours before sunset.

Irrigation can be made more precise and less wasteful by having activation triggered by a sensor measurement. In this technique, the timeclock creates a window of time when an irrigation cycle *may* occur while using one or more sensor measurements to determine the interval and duration that will occur *within that window*.

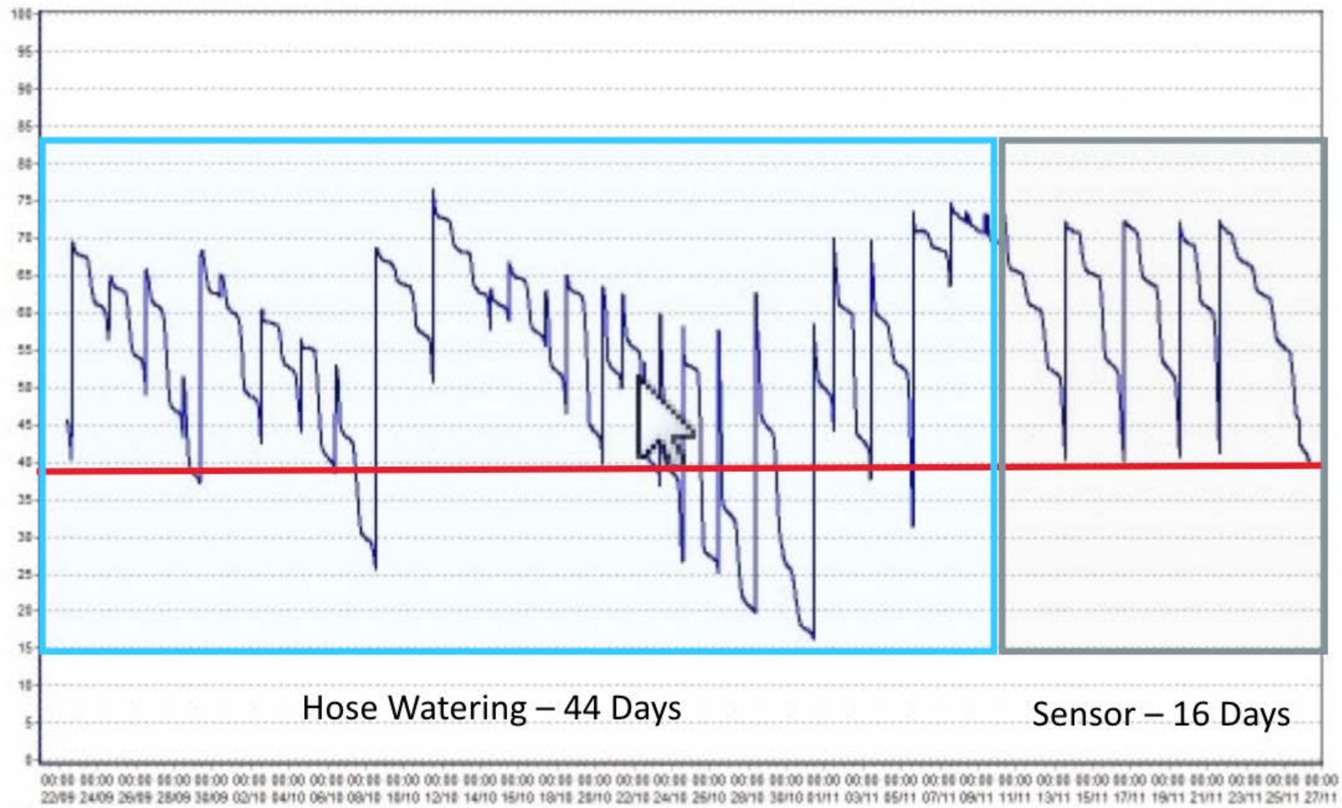
Variables that can activate irrigation may include an environmental measurement such as the amount of light accumulated since the last irrigation cycle (**light sum**), or a plant measurement. Plant measurements include leaf canopy temperature, moisture content or EC of the root zone, and plant weight. Further descriptions are provided below.

- **Soil moisture-based automation. Volumetric Water Content (VWC)** sensors are being adapted by growers for precision irrigation. These sensors consist of two or three rods (waveguides) that insert into the substrate and analyze the waveform of a small electromagnetic pulse. Some models also measure the temperature and EC of the root substrate. They are easy to install and move and come with their own hardware and logging software, though some models can be integrated into an advanced climate control system in order to activate irrigation. Disadvantages include the need for calibration with each substrate type, and, like most direct measurements, VWC sensors are only useful if the plant or plants being measured are representative of the entire crop.

The figure on the following page shows the VWC of a poinsettia crop over 60 days. During the first 44 days, greenhouse employees manually watered the crop with a hose according to their judgement of irrigation needs. For the final 16 days, a sensor triggered irrigation. The upward vertical spikes in the readings represent irrigations, which if done properly, would wet the soil mix to a minimum of 70% VWC. The downward drift of the readings represents the substrate drying over days. The horizontal red line represents the setpoint for irrigation initiation of 40% VWC. The sensor triggering the drip irrigation improved both the frequency and duration of the irrigation cycles.

IMAGE: GRODAN AND PRIVA

Figure 15. Volumetric water content of a poinsettia crop over 60 days, comparing hose watering for the first 44 days followed by sensor-based irrigation.



When VWC sensor-based irrigation is combined with pulse irrigation that does not saturate the soil, growers have even more control over soil moisture. The potential to reduce water consumption and eliminate most leachate is possible. Researchers from the University of Georgia demonstrated the ability to maintain eight blocks of plants at different VWCs (see graph to the right).[35] This level of precision could optimize irrigation in controlled environment agriculture as well as induce controlled drought stress to increase secondary metabolite production responsible for the taste, aroma, color, and/or medicinal value of plants.

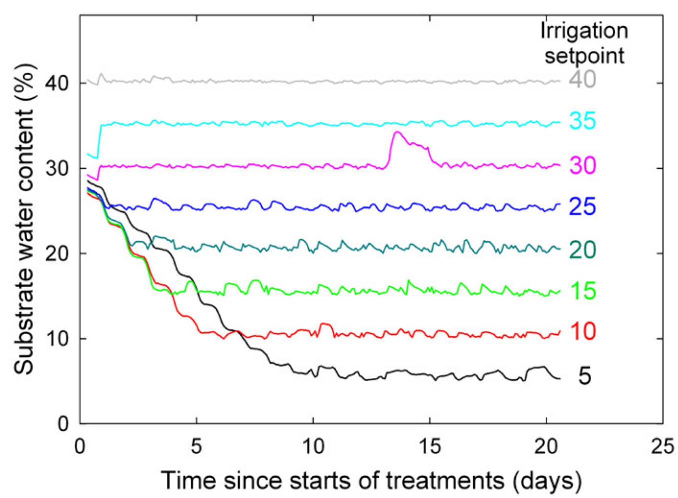


Figure 16. Substrate water content over time of eight blocks of plants each irrigated based on different setpoints monitored and controlled using soil moisture sensors.

35 Van Iersel, M. W., Dove, S., Kang, J., & Burnett, S. E. (2010). Growth and Water Use of Petunia as Affected by Substrate Water Content and Daily Light Integral, HortScience horts, 45(2), 277-282.

Working at full-crop scale with nursery growers, the Georgia research team also demonstrated a 70% reduction in water usage using VWC sensors brought a positive impact on the growers' bottom line: "Because of increased plant production and a decrease in the amount of water, fertilizer, pesticides, and fungicides needed by the plants, the systems typically pay for themselves in a year."[36] Follow-up research in a production greenhouse did not result in as many benefits, but the grower did expand the area of sensor-based irrigation following the study, indicating perceived value.

- **Evapotranspiration (ET) based automation using a light sensor**. Evapotranspiration is the sum of two processes: Water lost through transpiration through the leaf pores, and water lost by evaporation from the root substrate. Many irrigation strategies are based on measuring or modeling ET. Modeling ET by light sum is a common practice in horticultural substrate culture. This is a measure of the accumulated light since the last irrigation, and is particularly effective in matching the evapotranspiration rate, given that light determines 80%-90% of water uptake.[37] This method ensures irrigation is not activated as frequently during cloudy weather as in sunny weather in greenhouses.

Avoiding excess lighting reduces the transpiration needed to cool the plant, subsequently reducing irrigation and water waste. Recent research indicates yields may improve when light is "spread out" over the course of the day: Daily light energy of longer duration and lower intensity may improve yields more than a shorter duration of high-intensity light, even if both scenarios have the same **Daily Light Integral (DLI)**, or light sum.[38] Most plant species can't use all the bright sunlight they receive; their photosynthetic rate is limited, and beyond that light saturation point, the photons just cause the leaves to heat up, not create more sugars. Smart lighting programming may complement light sum-based irrigation.

- **Gravimetrics** is a time-tested method of making irrigation decisions. It is based on the principle that weight will be lost as a result of evapotranspiration. Growers use this technique by picking up pots by hand, with their experience allowing them to make a good decision based on the heft of the pot and the anticipated environmental conditions. Weight scales, either portable or dedicated, can be used to quantify this measurement. When choosing plants to measure, both the perimeter and interior ones should be evaluated. Often referred to as the "edge effect," evapotranspiration is often higher in plants on the table edge due to higher light and airflow.

Automating gravimetrics is a commonly used practice in the CEA vegetable industry, where uniform mono-cropping of tomato, pepper, and cucumber crops improves the method's reliability. Representative plants are grown on a dedicated scale, with the same irrigation system as the rest of the crop.

Importantly, gravimetric systems can automatically adjust irrigation frequency and duration during changes in weather, plant age, and plant growth stage. Fluctuations in moisture content and solution chemistry are reduced, eliminating stress. Disadvantages of the system include poor performance if the plants being weighed do not accurately represent the crop size or planting density, or if plants within the crop are highly variable.

- **Modeling evapotranspiration using multiple variables** requires a great deal of research, sensors, and computer calculations, so is most often conducted using an advanced climate control system. Commonly used variables in these models include light, temperature, airflow, and VPD. With the more recent advent of new sensors, leaf temperature and substrate volumetric water content (VWC) are increasingly added to model calculations. The physical properties of the substrate, such as water-holding capacity and container

[36] Melancon, M. (2013). UGA study shows soil-moisture sensor system slashes nursery water use by 70 percent. CAES Newswire. Retrieved May 5, 2023, from https://newswire.caes.uga.edu/story/4851/advanced-irrigation.html

[37] Irrigation de-mystified: Follow the rules of thumb and the plant performs as required. (2020). Hortidaily.com. Retrieved May 5, 2023, from https://www.hortidaily.com/article/9239852/irrigation-de-mystified-follow-the-rules-of-thumb-and-the-plant-performs-as-required/

[38] Alaviani, Seyyed & Van Iersel, Marc & Mohammadpour Velni, Javad. (2022). Optimal Supplemental Lighting Control for an Extended Photoperiod in Controlled Environment Agriculture. IFAC-PapersOnLine. 55. 639-644.

shape, as well as a running estimate of the leaf area, need to be accounted for. Great strides are being made to reduce human intervention in such models, as best exemplified by the Autonomous Greenhouse Challenge hosted annually by Wageningen University in The Netherlands, where research teams compete for best crop outcomes without entering the greenhouse room during the contest.

- **Irrigation rests and pauses.** Further time-based programming may be integrated into sensor-triggered programming by use of a minimum rest time and maximum rest time since the most recent irrigation. These define other windows in which irrigations are allowed to occur when other setpoints, such as light sum or plant weight, are reached. The minimum rest time keeps irrigation from happening too often and is particularly useful in large facilities to stagger irrigation cycles to maintain adequate water pressure. It also allows a suitable time for substrates to drain. Maximum rest times initiate an irrigation cycle even if the other trigger setpoints have not been reached. This is useful for low-light weather or seasons in greenhouses when a light sum has not yet been reached but the heat of the room has evaporated enough moisture from the substrate to require irrigation. In general, irrigation tends to occur closer to the minimum rest time during high-light conditions and closer to the maximum rest time in low-light conditions.

Lastly, the duration of an irrigation event can be programmed in two halves with an **irrigation pause** between them lasting a few minutes. This improves the absorption and lateral movement of the solution. Growers may find that by using a pause, they may be able to decrease the overall duration and cut back on leachate.

Reducing Use of Climate Control Water and Process Water

Conserving irrigation water is the subject of articles in trade and academic journals, and touted in public relations messaging by producers and advertisements of equipment and supply vendors. In contrast, the conservation of water by preventative maintenance scheduling is rarely documented or highlighted.

Climate control equipment such as boilers, chilling towers, and evaporative cooling pads for greenhouses and humidifiers for propagation rooms can produce a tremendous amount of waste. For example, evaporative cooling pads far exceed the water used for irrigation during summer months in a greenhouse. Sanitation washdown water results from daily cleaning of equipment and grow rooms required for safe food production. Process water such as produce washers and transit flumes can also become a waste stream. Reverse osmosis water purification often creates as much **reject water** waste as it does purified water. Designing out these sources of "hidden waste" is imperative for the industry, as these liquid wastes cannot economically be remediated and reused for irrigation.

SECTION 3 CONTENTS:

> Reducing Reject Water of Membrane Water Purification

> Reducing Waste of Greenhouse Evaporative Cooling Pad Systems

> Collecting Greenhouse Ceiling Condensate

> Reducing Water Used for Pest Control

Reducing Reject Water of Membrane Water Purification - Water treatment specialists agree that reducing this source of water waste is a priority for the CEA industry. Reverse osmosis, nanofiltration, ultrafiltration, and microfiltration are technologies for water purification that filter out ions and contaminants by passing pressurized water through a membrane with microscopic pores. These purification technologies are currently necessary tools for remediation but create a large amount of reject water, a concentrated brine that accumulates and fouls the membrane unless it is routinely rinsed away. Depending on the efficiency of the unit, a staggering 1-9 gallons of rejected waste may be created for each gallon of purified water. Alternatives to membrane technology will be discussed later in this guide, including the use of other, mostly pure water sources of rainwater and condensate from mechanical cooling and dehumidification.

Reducing Waste of Greenhouse Evaporative Cooling Pad Systems - Greenhouse fan and pad systems operate off the principle that, thermodynamically, heat is required for evaporation. Fan and pad systems remove heat from the air by drawing it through a wet cellulose pad as water evaporates off its surface, removing up to 8,700 BTUs of heat for each gallon the pad and fan system uses.[39] Fans on the other side of the greenhouse exhaust air out, pulling fresh air in through louvers behind the cellulose cooling pad. A pump distributes a thin coat of water over the pad. Some of the water evaporates to cool the greenhouse, while the remaining water is recaptured in a reservoir to be recirculated back to the pad. A float system adds fresh water to the reservoir as needed to keep it full. The efficiency problem with this system arises because ions, often calcium and magnesium but varying according to source water, are left in the water during evaporation and concentrate to a level that would cause a scale build-up on the evaporative pads if some of this brine is not bled off the reservoir. Every time the pump turns on, some of the pumped water is diverted to a drain to the waste stream.

Evaporative cooling consumes an immense amount of water. An 8-month study of water use in a Tucson, Arizona greenhouse determined that the evaporative pad and fan cooling system used 185% of the water volume required for irrigation.[40]

The flow rate of these **bleed-off** valves typically is set to drain 1 gallon per hour per linear foot of pad 4 feet tall, or 1.5 gal/hour/ft if the pad is 6 feet tall (assuming a 6-inch thick pad).[41] Growers can test this bleed rate by redirecting the flow into a bucket with a known volume. For example, a 50-foot long, 6-inch thick pad measuring 6 feet high, starts with a bleed-off rate of 75 gallons/hour. That 75 gallons/hour will fill a 5-gallon bucket in 6 minutes and 15 seconds. If the bleed is greater than calculated, the difference is the amount of water that is being drained to waste for no purpose.

If the bleed-off valve is poorly set or has changed over time through vibration, it is not uncommon to find it set at three times this recommended rate. Over a summer, this may equate to over 162,000 gallons of unneeded waste from just this 50-foot pad wall–nearly 4.2 million gallons of wasted water per greenhouse acre. Broken or poorly adjusted float valves also contribute greatly to waste. These are among the best examples of the value of preventative maintenance that any employee could perform. Likewise, pad and fan systems represent a common source of leaks that contribute to this waste.

Depending on the chemistry of the primary water, some modern greenhouses are now being built with evaporative pad and fan systems fed by reverse osmosis-treated water, eliminating the need for bleed-off since this water source has no ions that would concentrate in solution. However, this pre-treatment would create a waste stream from the RO process. Research needs to be done to examine the practicality of using rainwater or HVAC condensate to feed evaporative pad systems. Safety is a priority, as contaminants can potentially be released into the air from the evaporative pad surfaces. Also, organisms can thrive in stagnant reservoirs, including human diseases such as Legionairre's Disease. Water testing results could determine the best solution to pre-treat water used to refill evaporative pad reservoirs.

39 Bartok, Jr., J. W. (2016). Fan and Pad Evaporative Cooling Systems. Center for Agriculture, Food, and the Environment. Retrieved May 5, 2023, from https://ag.umass.edu/greenhouse-floriculture/fact-sheets/fan-pad-evaporative-cooling-systems

40 Sabeh, N., Giacomelli, G., & Kubota, C. (2011). Water Use in a Greenhouse in a Semi-Arid Climate. Transactions of the ASABE, 54(3), 1069–1077.

41 Gates, R. (2019). Evaporative Cooling Pads – Maintenance for a Longer Life. Illinois Extension. Retrieved May 5, 2023, from https://extension.illinois.edu/blogs/ag-engineering-update/2019-06-11-evaporative-cooling-pads-maintenance-longer-life

Another potential improvement would be bleeding off the reservoir only when needed, with a valve operated by a sensor monitoring EC or alkalinity, rather than the bleed-off occurring the entire time the pad circulation pump is operating. We are aware of no such commercial systems that are built to do so.

Larger HVAC systems used for cooling buildings that leverage cooling towers operate off the same principle as evaporative pads and also create a waste stream, sometimes referred to as **blowdown water** (rather than bleed-off water).

Collecting Greenhouse Ceiling Condensate - Modern greenhouses may also use smart programming to reduce relative humidity and increase VPD by allowing roof glass to cool below the dewpoint of the air, causing condensation to form. The condensate is then collected in a specialized gutter at the greenhouse furrow and directed to storage and remediation. This procedure is best conducted at night with careful control of the energy curtain(s) and air temperature.[42] One disadvantage is the condensate may have residues from pesticides, including sanitizers.

Reducing Water Used for Pest Control - Insect and disease control efforts not only use water, but any waste solutions are challenging to treat and potentially harmful to plants or aquatic life if discharged into the environment. Another best practice for indoor farms and greenhouses is using **foaming equipment** when applying disinfectants. Foaming equipment increases reaction time on vertical surfaces without multiple applications. Similarly, if pesticides are used in the facility, consider formulations that can be applied using an **ultra-low volume sprayer** or **cold fogger**, as they dramatically reduce the water required and eliminate waste.

Figure 17. From top: evaporative cooling pad and reservoir; scale and biofilm accumulation on a pad; empty reservoir showing PVC-pipe bleed-off feeding into a drain pipe, close up of the bleed-off flow following adjustment.

42 Geelen, P. A. M., Voogt, J. O., & Van Weel, P. A. (2018). Plant Empowerment: The Basic Principles. LetsGrow.com.

SECTION 04

Recapture of Water

The first step in remediating and reusing water is to capture it. Careful planning is needed to account for the required plumbing, transfer and treatment equipment, and storage of recaptured water. The footprint and layout of the entire facility will be significantly impacted, not just the water treatment area. Retrofitting such systems after production has begun is very challenging.

Capturing Rainwater - If allowed by your state or province and in abundance, rainwater is a vastly underutilized source of irrigation water. Water quality is typically good if it has not come in contact with the ground or been exposed to industrial pollution or fallout.[43] Bird droppings and other animal waste contaminating the reservoir will require operators to disinfect the rainwater before use on food crops. Coastal areas may have elevated levels of sodium, which also will need to be reduced via purification. Rainwater contaminated by toxic chemicals called per- and polyfluoroalkyl substances, or **PFAS**, is now a global problem, according to newly published research, so it may need to be addressed in the future.[44]

SECTION 3 : CONTENTS

> Capturing Rainwater

> Capturing Irrigation Leachate

> Managing Leftover Leachate at the End of the Crop Cycle

> Capturing Condensate from Cooling and Dehumidification Equipment

> Capturing Washdown Water

> Capturing Compost Wastewater

43 UMass Extension Greenhouse Crops and Floriculture Program. (2017). Water: Supply and Sources. Center for Agriculture, Food, and the Environment.

44 Cousins, I. T., Johansson, J. H., Salter, M., Sha, B., & Scheringer, M. (2022). Outside the Safe Operating Space of a New Planetary Boundary for Per- and Polyfluoroalkyl Substances (PFAS). Environmental Science & Technology, 56(16), 11172–11179.

Rain is most easily captured from gutter-connected greenhouses or guttered buildings containing indoor farms. A device known as a roof washer diverts the initial flush of water to waste, as it is often full of debris and dirt from the roof and gutters. Other basic components include a storage tank, inflow pipes, overflow pipes, and a water diverter in case the tank reaches capacity. The overflow should not be allowed to flood adjacent properties.

Once disinfected, the nearly pure rainwater can be used in the normal irrigation lines to reduce water consumed from other sources. Rainwater is rarely adequate as a sole source of water because of seasonality and storage, but it is effective at diluting the quality problems of other water sources.[45] This could potentially reduce the operating cost of water treatment, as cleaner water improves the efficiency of these systems. Use of rainwater is routinely done in The Netherlands, where growers are required to have a storage capacity of at least 500 cubic meters (m^3) of rainwater per hectare of production facility (53,450 gallons/acre), which can provide for up to 65% of irrigation water needs.[46] At Duijvestijn Tomatoes near Delft, Netherlands, the 36-acre greenhouse range uses rainwater as its only source for irrigation.

Note that stormwater runoff that has contacted the ground is not typically a target for treatment and re-use for irrigation in controlled environment facilities growing food, though in floriculture operations that runoff may be directed to ponds holding irrigation leachate. Many municipalities require that the first two inches of a rainfall event be held on-site in stormwater basins rather than let it drain to neighboring properties.

The first step in planning for rainwater capture is calculating the volume of storage required. A 1-inch rainfall on an acre of greenhouse roof yields 27,100 gallons (100 m^3/hectare per centimeter (cm) of rainfall).[47] Historical weather data can help determine rainfall amount patterns throughout the year. To calculate the volume of gallons that can be collected, multiply the square feet of the greenhouse or indoor farm building by 0.4.[48]

Another tool for planning rainwater capture is the Water Flow Model created by the University of Wageningen in The Netherlands. This sophisticated model calculates crop evaporation based on local climate (solar radiation) and the amount of primary water needed plus rainwater, which can then be used to calculate rainwater storage requirements.[49] A later section of this guide will provide advice for designing water treatment and storage areas.

Depending on the volume desired for storage, containers or earthen basins can be used. Container types include concrete septic cisterns, polyethylene tanks, or lined, corrugated steel tanks. Concrete cisterns and plastic tanks are typically limited to 15,000 gallons. They may be above ground or buried. Metal tanks are shipped as panels and assembled on-site, either bolted or welded together. Their capacity can be over a million gallons.[50] Liners for these tanks will need replacement every few years, though local regulations may require it more frequently. Earthen basins are typically used for capacities of 1,500 m^3 (400,000 gallons) or more, either dug in the ground or bermed above ground where water tables are high.[51] Depending on soil type, ponds can be lined or unlined. They also may be covered in warmer regions where evaporation rates are high.[52] Consideration should be given to the control of mosquito and waterfowl populations for uncovered storage, as these could be nuisances or sources of food-borne illness. Ponds are not prevalent in the western U.S. due to evaporation. Though most storage in the U.S. is done with basins, underground aquifers are used in some regions, including parts of Northern California that are not attached to the Colorado River basin.

A best practice for rainwater capture, as well as water circularity in general, is to consult industry professionals with experience specific to horticulture operations. They will have resources to account for local regulations, geology,

45 Raviv, M., Lieth, J., & Bar-Tal, A. (Eds.). (2019). Soilless Culture: Theory and Practice (2nd ed.). Elsevier.
46 Raviv (2019)
47 Bartok, J. (2014). Weighing the perks of rainwater collection. Greenhouse Management. Retrieved May 5, 2023, from https://greenhousemag.com/article/gm1114-rainwater-collection-systems/
48 Bartok, J. (2014).
49 Waterstromen | Wageningen UR. (n.d.). https://www.glastuinbouwmodellen.wur.nl/waterstromen/Register.aspx
50 Zylstra (2021)
51 Raviv (2019)
52 Zylstra (2021)

weather, and equipment appropriate to controlled environment agriculture. For example, regions such as northern California with uneven precipitation patterns may require larger storage capacity.

Likewise, the construction of earthen basins should be done under the supervision of a local professional familiar with local soils and regulations. Cooperative Extension service agents at the land-grant university (also known as a university Extension) in your state can direct growers to regional weather data, geological information, and other resources.

As noted earlier, the use of rainwater–where suitably abundant–in evaporation pad reservoirs for greenhouses would greatly reduce the need for bleeding the reservoirs due to salt accumulation, thereby saving a significant amount of water in the summer months.

Capturing Irrigation Leachate - Whether called effluent, run-off, or drain, irrigation leachate is the solution that is unabsorbed by the root substrate and drains out of the container. It can also be equated with the "**dump water**" that is discarded from hydroponic systems after excess ions or particulates have accumulated. Though the two are often regulated the same, one expert notes there can be exemptions for regulating dump water if it can be represented as "irregular and infrequent incidental discharge."[53] As stated earlier, leach fractions are most often 10%-20% of the irrigation volume applied, but can be as high as 60% in some circumstances.

Capturing leachate typically involves growing plants on solid tables, gutters, or troughs where the solution can be gravity fed to a drain pit via a collection pipe. From there, the solution is pumped to a water treatment area where it is filtered, disinfected, purified (or mixed with a purified water source), and then recharged with nutrients prior to reuse. Site- and crop-specific filtration, disinfection, and purification treatments are detailed in later sections of this guide.

Unless the facility has flood floors specifically designed for ebb-and-flood on a high volume scale, with operational techniques to prevent contamination, letting irrigation water hit the floor should be discouraged. Depending on how a jurisdiction classifies a building, a floor drain may need to be piped to a sanitary sewer, disqualifying the solution from reuse.

Managing Leftover Leachate at the End of the Crop Cycle - What can be done with the volume of leachate remaining when a crop is terminated? One recommendation involves smart programming of the water treatment system in the final 1-2 weeks of growth.[54] The percentage of purified water added to the solution during treatment is increased, while the duration of irrigation is decreased, resulting in the emptying of the leachate storage tank. Although nutrient and water demands are often lower (depending on crop species), careful consideration of crop needs should be maintained so that quality is not sacrificed with this method.

Experienced horticulture water treatment specialists define other best practices. When calculating the storage size and pump capacity of your systems, design toward the maximum load. In rockwool slab cultivation, for example, the initial wetting of the slab is done prior to drainage slits being cut in the bottom of the plastic wrapping. When the slits are made, a lot more solution drains from the slabs than during normal irrigation cycles. For cultivation using coconut coir-based substrates, the initial wetting often releases tannins that turn the water brown and may contain excess ions of sodium, chloride, and potassium. The presence of sodium may preclude this first flush of leachate from re-use.

Irrigation leachate should be collected and stored separately from other water sources. It is vital to protect plants from contaminants that may exist in these other sources, and the treatment of irrigation leachate is often the most expensive to perform, so increasing the volume by co-mingling with other types of water is typically not cost-effective. Lastly, experts advise that by collecting leachate, you are often statutorily obligated to treat it before discharging it into the environment, so have a plan in place–and the equipment to carry it out–before the capture.

Capturing Condensate from Cooling and Dehumidification Equipment - Like rainwater, condensate from air-conditioners and dehumidifiers is a massive untapped resource for free, high-quality water, often with low

53 Zylstra (2021)
54 Lee (2016)

regulatory hurdles. Condensate forms on chilled coils of air conditioners and dehumidifiers–whether stand-alone dehumidification units or integrated into advanced HVAC units (designated as HVAC-D). Typically, the condensate is drained to waste or allowed to evaporate. Given that plants transpire up to 99% of the water they uptake, capturing this water on condensation coils is another way of "closing the loop" of the indoor water cycle and reducing the water footprint of the entire facility.

Research published in 2020 showed condensate water recovery accounted for 67% of the annual water demand for lettuce in a vertical farm.[55] Other vertical farm producers have reported conserving 80% of their water through condensate reclamation.[56]

Condensate from HVAC, HVAC-D, and standalone dehumidifiers is collected in a drain pan and gravity fed (or pumped) to a drain through plumbing pipes. Redirecting this condensate stream to storage and treatment in a water treatment area is often done using condensate pump stations with level controls and reliable pumps for increasing pressure.

Hazards of condensate use include contamination with metals, corrosion inhibitors, and biocides, which could lead to serious plant damage if the condensate is not remediated before use in irrigation. Near-pure water can corrode pipes and lead to the leaching of copper or aluminum from cooling coils, galvanized drain pans, and piping into the solution. Biocides are sometimes added to the drain pans as part of scheduled maintenance to control algae, bacteria, and biofilm development. Coated condensate coils and non-corrosive pans and plumbing are recommended. Best practices would include testing condensate and developing SOPs to avoid biological growth without the use of chemicals. Metals that are not absorbed by plants, such as copper, concentrate in recirculated irrigation systems, with levels increasing over time.

Figure 18. Rooftop HVAC/Dehumidification unit with insulated ductwork and condensate drain.

Capturing Washdown Water - Washdown water includes cleaning solutions used for tables, pots, floors, walls, tools, and equipment. It also includes gray water from dishwashers and pot washers, as well as utility and bathroom sinks. Water for cleaning and conveyance of harvested vegetables and fruits would most likely be captured through floor drains connected to local septic fields or a municipal water treatment facility. Though typically not re-used, CEA facilities seeking to reach Minimum Liquid Discharge status should remediate or evaporate this waste onsite. Contaminants will be varied and unpredictable. They may include soaps, detergents, stabilized chemistry from various operations, oils, grease, and pesticide residues, making treatment decisions challenging. The presence of organic matter further complicates treatment as it promotes biological activity. As will be discussed in Section 7, biological remediation may be a useful technology for treating washdown water before release to the environment.

IMAGE: INSPIRE TRANSPIRATION SOLUTIONS

55 Pacak, A., Jurga, A., Drąg, P., Pandelidis, D., & Kaźmierczak, B. (2020). A Long-Term Analysis of the Possibility of Water Recovery for Hydroponic Lettuce Irrigation in Indoor Vertical Farm. Part 1: Water Recovery from Exhaust Air. Applied Sciences, 10(24), 8907.

56 Hansen, J. (2018). Slash your Water Use by 50% or More. CBT. July 2018

Capturing Compost Wastewater - Some large greenhouse operations compost their unused plant material, root substrates, and other solid wastes. **Contact water** (water that has come into contact with composting piles) can contain nutrients and contaminants that preclude it from being allowed to enter nearby surface water. Typically, a **National Pollution Discharge Elimination System (NPDES)** is needed for treated wastewater discharged, including compost contact water, to state water bodies. A best practice is to collect contact water in a properly lined basin and then reintroduce it into compost piles with pumps and an irrigation system. Storm water should be diverted from the composting area and kept separate from contact water. Local and state regulations should be reviewed to verify best management practices and required protocols.

An excellent source of information on commercial-scale composting is the "Michigan Compost Operator Training Guidebook."[57] According to the U.S. Composting Council:

*"**Microorganisms** in compost have been used to break down a variety of contaminants, such as chlorinated hydrocarbons, wood preservatives, solvents, pesticides, petroleum products, and even explosives. What's more, even non-organic pollutants, such as lead and other heavy metals, can be remediated with compost. "*[58]

Further research should be conducted to determine if CEA wastewater streams, particularly brines or washdown water that cannot be easily remediated, could be applied to compost operations for remediation, given the need to keep the material moist for biological activity.

A best practice is to plan for future regulation of water usage. Some producers design capacity for it during construction planning as a hedge against future water scarcity or discharge regulation.

57 Chardoul, N., O'Brien, K., Clawson, B., & Flechter, M. (Eds.). (2015). MICHIGAN COMPOST OPERATOR TRAINING GUIDEBOOK: Best Management Practices for Commercial Scale Composting Operations. Michigan Recycling Coalition.

58 U.S. Composting Council. (2008). USCC factsheet: Using Compost Can Reduce Water Pollution.

SECTION

05

Physical Water Remediation Systems

In this section, we will introduce the technology systems with a physical mode of action used to remediate source water, irrigation leachate, climate control water and processing water, and provide references for further detail. Every CEA operation will use one or more of these physical technologies, as filtration is almost always necessary to protect equipment from clogging and because it is a vital pre-treatment for other technologies. Physical technology will typically be combined with chemical technologies in order to filter particulate, adjust pH, purify, disinfect and recharge the nutrient balance of irrigation water. Likewise, they will be combined with chemical or biological technologies to treat water for discharge.

Tempering - Raising the temperature of water may be useful for CEA facilities in order to protect plant roots from cold water and to maximize efficiency of reverse osmosis purification. Root zone temperature below 18°C (64°F) impairs nutrient uptake and growth for most crops. (Note that groundwater temperature is cooler than this in every state in the U.S. except those along the Gulf Coast.) Reverse osmosis purification membranes are rated for

SECTION 5 : CONTENTS

> Tempering

> Particulate Filtration

> Granular Activated Carbon Filtration

> Reverse Osmosis Membrane Purification

> High-Efficiency Reverse Osmosis

> Electrodialysis

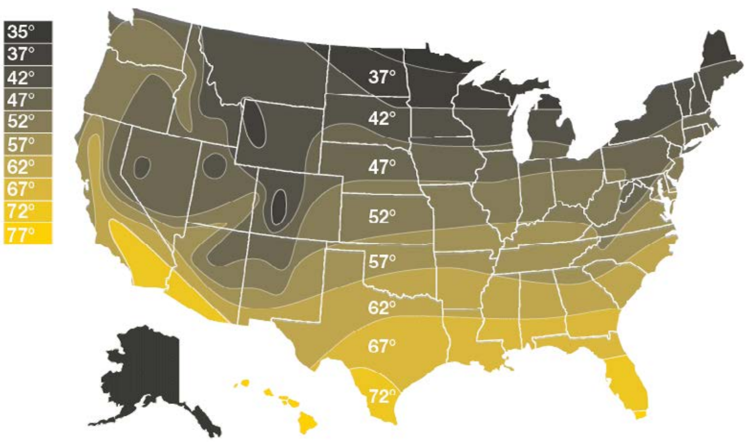
> Evaporators

> Vacuum Distillation

> Technology on the Horizon - Cold Plasma

their efficiency using water of 25°C (77°F), with cooler temperatures causing membrane pores to shrink, reducing efficiency and increasing water waste. Many CEA facilities warm water to room temperature by pumping it into storage tanks located indoors. Heat exchangers, solar heaters, or heat recovered from other systems can also be used to warm water.

Figure 19. Groundwater temperature map of the U.S.



Particulate Filtration - Every irrigation system requires particulate filtration for control of inorganic minerals such as sand, clay or silt, as well organic debris and algae. There are many different types of filter systems that screen particulates from coarse to fine, including screen filters, rapid sand filters, cartridge filters, disc filters, paper or fabric filters. Particulates can clog nozzles, emitters and seals in irrigation equipment. They can also foul reverse osmosis membranes, and greatly reduce the effectiveness of oxidizers and ultraviolet light (UV) disinfection, as will be described in the next section.

Municipal water is mostly free of sediment, organic load, and algae, but other sources usually contain much more suspended particles. Well water may contain silt, as does surface water from lakes and streams, which may worsen seasonally as well as after a heavy rain. Surface water may also contain algae and pathogens. Stagnant ponds may have microbial contamination, algae and high turbidity (cloudiness from suspended matter). Pond water may also have multiple particulate types, requiring multiple stages of filtration.

Water testing should be done to determine the required filtration that minimizes pressure loss and accounts for your maximum daily water usage and quality needs. The University of Massachusetts reports maximum usage for greenhouses at 0.3-0.4 gallons per square feet of growing area per day (gal/ft^2/day), and that filter capacity ranges from 10-1,000 gallons per minute (gpm).[59] Note that membrane filtration will be discussed later in this section.

Figure 20. Sediment cartridge filters in blue colored casings, upper right.

Granular Activated Carbon Filtration - Granulated Active Carbon (GAC) filters are effective at removing high concentrations of chlorine and fluoride from municipal water that might otherwise damage plants in hydroponics. University testing has shown their effectiveness in removing herbicides from runoff ponds and pesticides and growth regulators from irrigation leachate if recycled.[60,61] The studies also demonstrated the ability to use GAC for removal of sanitizers, quaternary ammonium chloride, sodium hypochlorite, and a combination of hydrogen peroxide and peracetic acid. These attributes make GAC a good technology for treating discharge water for regulatory compliance. It may also be a useful remediation for produce-wash water containing disinfectants, and,

LEFT IMAGE: BRADLEY CORP

59 Bartok, J. (2009). Protecting Your Water System with a Good Filter. Center for Agriculture, Food, and the Environment. Retrieved May 6, 2023, from https://ag.umass.edu/greenhouse-floriculture/fact-sheets/protecting-your-water-system-with-good-filter

60 Fisher, P., Grant, G., & Raudales, R. (2019). Clean Up Your Water with Carbon Filtration - Greenhouse Product News. Greenhouse Product News. September 2019.

61 Grant, G., Fisher, P. B., Barrett, J. H., & Wilson, P. C. (2019). Removal of Agrichemicals from Water Using Granular Activated Carbon Filtration. Water Air and Soil Pollution, 230(1).

according to the EPA, to treat rainwater for PFAS.[62] One limitation of GAC is the contact time required to purify, which can be up to 15 minutes for pesticide removal, so planning the size of the system is crucial.

Reverse Osmosis Membrane Purification - When two solutions of different purities–"pure" and "contaminated"–are separated by a semipermeable membrane, osmosis occurs. Water molecules from the pure side move through the membrane to equalize the water concentration (purity) of both sides. In reverse osmosis, pressure is applied to the contaminated side to force the water through the membrane. If the pores of the membrane are too small for any of the contaminants to get through, this leaves all the contaminants on the pressurized side and only pure water on the other side. In a CEA context, the contaminants are the inorganic (ions, etc.) or microbial (e.g. plant and human pathogens) found in water. These contaminants are left behind on the pressurized side of the membrane, along with some of the water, to be flushed away as waste along with the rinsate used to routinely clean the membrane pores. This waste stream (referred to as reject water, or brine) is not suitable for irrigation because of the high ion concentration, and discharge is often highly regulated. The pure water from the unpressurized side of the membrane is reused for irrigation or other purposes.

Reverse osmosis (RO), **microfiltration** (MF), **ultrafiltration** (UF) and **nanofiltration (NF)** are all pressurized membrane purification systems. They differ in the pore size of the membrane and the pressure applied, with pores becoming smaller and pressure used increasing from MF→UF→NF→RO, with RO creating the most purified water. Importantly, these pressurized membrane systems also differ in the amount of reject water they create. In the most inefficient systems, a facility may be creating nine gallons of brine waste for every gallon of purified water. This is unconscionable if the industry is to secure consumer trust in environmental resilience. A best practice is to minimize the reject water from water purification systems by verifying the system's recovery rate. Membrane filtration systems are typically specified for their recovery rate in percentage, the higher the value the better. Membranes do not filter all elements or chemicals equally. As seen in Figure 21, boron is not filtered out as efficiently.

Figure 21. Manufacturer estimate of reverse osmosis rejection percentages of elements and chemicals, using thin film composite membrane.

Aluminum	97-98%	**Nickel**	97-99%
Ammonium	85-95%	**Nitrate**	93-96%
Arsenic	94-96%	**Phosphate**	99+%
Bacteria	99+%	**Polyphosphate**	98-99%
Bicarbonate	95-96%	**Potassium**	92%
Boron	50-70%	**Pyrogen**	99+%
Bromide	93-96%	**Radioactivity**	95-98%
Cadmium	96-98%	**Radium**	97%
Calcium	96-98%	**Selenium**	97%
Chloride	94-95%	**Silica**	85-90%
Chromate	90-98%	**Silicate**	95-97%
Chromium	96-98%	**Silver**	95-97%
Copper	97-99%	**Sodium**	92-98%
Cyanide	90-95%	**Sulphate**	99+%
Ferrocyanide	98-99%	**Sulphite**	96-98%
Fluoride	94-96%	**Zinc**	98-99%
Iron	98-99%		
Lead	96-98%	**Insecticides**	97%
Magnesium	96-98%	**Detergents**	97%
Manganese	96-98%	**Herbicides**	97%
Mercury	96-98%	**Virus**	99+%
TDS (Total Dissolved Solids)	95-99%	**Hardness**	93-97%

High-Efficiency Reverse Osmosis (also known as high-performance RO) uses multiple passes of the feed water and the reject water through one or more membranes to reduce the final amount of reject water. These highly efficient systems are costly but consume less energy than reverse osmosis alone and are very effective in reducing water waste. Some manufacturers combine ultrafiltration, nanofiltration and reverse osmosis membranes in such a way to recapture 50% of the nutrients in the water while removing most of the sodium, the ion that is most problematic to plant health in recirculating systems. These high-performance systems may also be equipped with sensors on the membranes so that rinsing occurs only as necessary, which in turn reduces the amount of reject water. Recovery rates can be as high as 90%. For more information, refer to a reputable horticulture water treatment specialist and the 'Reverse Osmosis Optimization' guide by the U.S. Environmental Protection Agency.[63] Improved recovery rate can also be enhanced with higher quality membranes and optimum flow configuration.

IMAGE: PURE WATER PRODUCTS

62 Reducing PFAS in Drinking Water with Treatment Technologies | US EPA. (2022, November 28). US EPA. https://www.epa.gov/sciencematters/reducing-pfas-drinking-water-treatment-technologies

63 McMordie Stoughton, K., Duan, X., & Wendel, E. (2013). Reverse Osmosis Optimization. U.S. Dept of Energy.

Electrodialysis - **Electrodialysis** moves ions (nutrients or contaminants like sodium) across membranes to purify water as does reverse osmosis systems, but with two important differences: 1) it moves the ions through a membrane by an electrical potential difference created by electrodes rather than using pressure to move water through a membrane, and 2) it has a much higher recovery rate than standard RO systems. This is relatively new technology in our industry. At least one horticulture equipment company has combined electrodialysis with ion-selective membranes to filter a significant portion of the sodium (Na) from leachate while leaving much of the fertilizer nutrients in the solution for re-use. *This is a significant advancement*, as the challenge in selectively filtering sodium out of leachate has always been that potassium was also lost. The company reports a water recovery rate of 95% and, since pressure is not applied to the solution, energy cost from pumps is significantly reduced.

Evaporators - Some heavily contaminated liquid waste is difficult to be disposed of due to local regulations, including reject water, water containing detergents and chemical residues, and boiler blowdown water. Evaporators are pieces of equipment that reduce large volumes of liquid waste to small volumes of solid waste, which may be cost-effective compared to having the liquid waste hauled to a licensed disposal site. Heat is used to vaporize the wastewater, ensuring no liquid waste is discharged from the facility. In some cases, the vapor is recaptured as condensate on cold coils and recirculated in the facility. Disadvantages include high operating costs and carbon emissions if the equipment is powered by fossil fuels. At least one company has commercialized a wastewater treatment evaporator powered by solar energy.[64]

Vacuum Distillation - Vacuum distillation is a process by which water is subjected to vacuum pressure and vaporized at a temperature lower than the normal boiling temperature of water. Several water treatment experts noted this technology is a much more energy-efficient solution for treating wastewater than an evaporator, and fossil fuels are not used. Further, due to the low operating temperature, vacuum distillation units generally require less maintenance and last longer than atmospheric evaporators as they experience less thermal wear. Pure water is created which could be fed back into the cultivation system. Unlike evaporators, though, vacuum distillation does not reduce the liquid to a solid, but to a slurry of approximately 5-15% of the original waste volume. This slurry is typically hauled away by a licensed disposal company.

Figure 22. Selective sodium removal via electrodialysis.

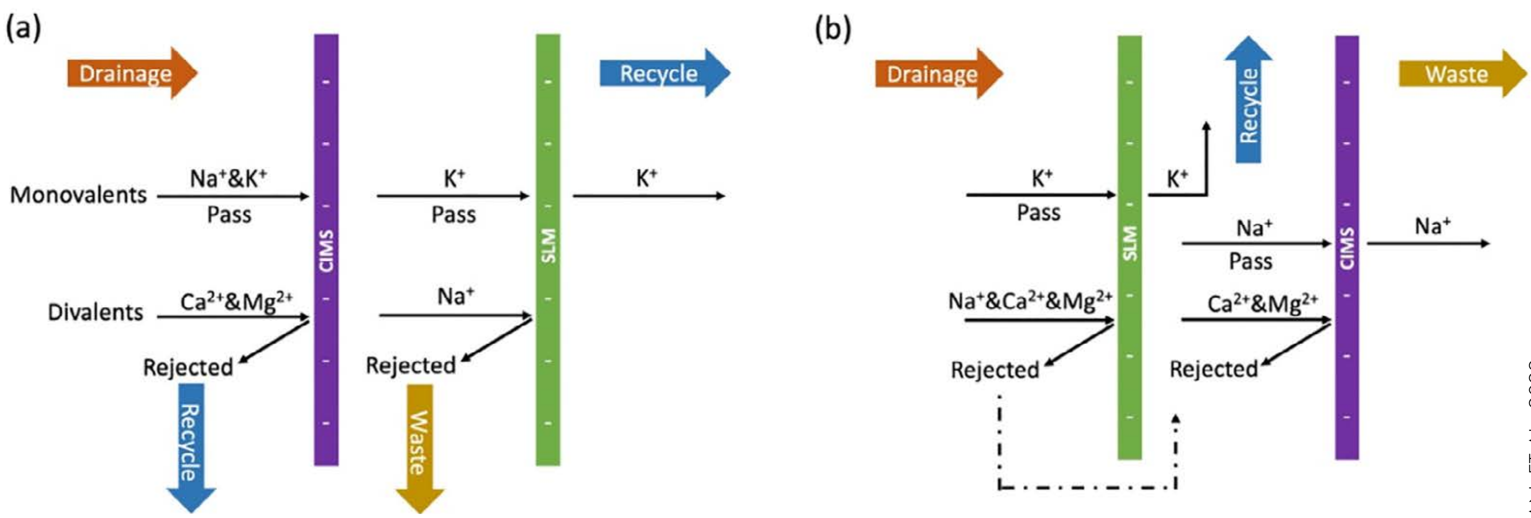


IMAGE: QIAN, ET AL., 2022

64 Wastewater treatment evaporators powered by solar energy. (2021). Condorchem Envitech. June 2021.

Figure 23. Vacuum distillation unit.

Technology on the Horizon - Water treatment companies are beginning to commercialize **cold plasma disinfection technology**, a chemical-free method of creating an ionized gas from oxygen. This plasma is passed through water, adding both dissolved oxygen and reactive oxygen species with high disinfection potential.[65]

[65] Ghernaout, D., & Elboughdiri, N. (2020). Disinfecting Water: Plasma Discharge for Removing Coronaviruses. OAlib, 07(04), 1–29.

SECTION
06

Chemical Water Remediation Systems

In this section, we will introduce chemical technology used to remediate source water, irrigation leachate, climate control water, and processing water, and provide references for further detail. As the chart on chemical water treatment technology at the end of the section indicates, some of the most effective disinfection results from a combination of two chemistries: ozone and peroxyacetic acid, or either of the two with UV-C light.

pH Adjustment - As most growers understand from experience, pH must be maintained within an appropriate range in order for dissolved nutrients to be in the appropriate chemical form for root uptake. Typically this range is 5.5-6.3, depending upon the cultivation system and the species. CEA facilities utilizing recirculating systems for nutrient solutions will incorporate acids or bases into the reservoirs to control pH, ideally with automated pumps responding to submersed sensors. Bases include potassium hydroxide and potassium silicate, while acids include

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> pH Adjustment
> Alkalinity Adjustment
> Hardness Adjustment
> Ion Exchange Resin Purification
> Deionization
> Chlorine Disinfection
> Chlorine Dioxide Disinfection
> Electrochemically Activated Water
> Copper Ionization Disinfection
> Ultraviolet Light Disinfection
> Ozone Disinfection

phosphoric acid, acetic acid, and sulfuric acid. Citric acid and fulvic acid are sometimes used in CEA, but these organic compounds may promote microorganism growth in the solution. A best practice is to have sensor redundancy to monitor pH adjustments. Operations that do not recirculate their irrigation will often adjust pH using a separate injection head of their fertigation system designed to withstand corrosive acids.

Alkalinity Adjustment - As groundwater flows through bedrock containing limestone or dolomite, calcium carbonates and magnesium carbonates dissolve into it. While hardness is a measure of the calcium, magnesium, and iron, **alkalinity** is the measure of ions such as carbonates that affect pH buffering. Alkalinity is a measure of a solution's ability to neutralize acid. In practical terms, a little alkalinity is beneficial. It gives water the ability to maintain a stable pH in the presence of acidic fertilizer or other chemicals dissolved in fertigation formulations. This stabilizing ability is also referred to as a solution's **buffering capacity**.

Too high of alkalinity can cause carbonates to accumulate in the root substrate and pH to rise, triggering nutrient deficiencies. When recirculating in hydroponic systems, carbonates will concentrate over time and cause scale to form. Since acids and carbonates neutralize each other, a management option for alkalinity is to inject acid into it. This can be accomplished by using acidic fertilizers in some cases, or direct injection of phosphoric, nitric or sulfuric acid. (For help choosing the right acid and the correct rates of addition for horticultural substrate culture, use the free Alkalinity Calculator from e-GRO.)

Purification is another means of eliminating alkalinity. However, purified water such as reverse-osmosis water, deionized water, and distilled water will have no carbonates to buffer against pH change, resulting in what growers often refer to as "chasing pH."

A best practice is to work with your fertilizer provider to determine appropriate formulations and required pre-treatment according to laboratory water quality analysis.

Hardness Adjustment - Water hardness is the measurement of the concentration of total divalent ions of calcium, magnesium, and iron present in water. Hard water causes scale to accumulate in water systems, reducing flow and clogging orifices. Hard water can foul membranes used for water purification. If applied to leaves, hard water can also leave unsightly residues on plants that can sometimes be confused for powdery mildew.

Hardness and alkalinity (more below) are reported in the same units, (calcium carbonates or bicarbonates). While they are somewhat related, hardness refers to the ions (Ca, Mg, etc.) attached to the carbonates, and alkalinity is a measure of resistance to acidity and measures the concentration of carbonates.

Water softening, or **demineralization**, uses a cation exchange resin bed to exchange calcium, magnesium, and iron for other positively charged ions, typically sodium or potassium. Demineralizing does not increase the overall salinity of the water, it *exchanges* one type of salt ion with another.

Figure 24. Clogged drip irrigation emitters.

IMAGE: SILVER BULLET

Table 7. Comparison of water attributes of high pH, alkalinity and hardness.

	High pH	Alkalinity	Hardness
Definition	Solutions with a pH value >7. A basic solution, as opposed to acidic.	Ability of the water to resist pH changes that occur due to acids. "Buffering capacity."	Amount of Ca and Mg in the water
Cause	Higher concentrations of OH^- ions than H^+ ions	Carbonates from limestone or dolomite bedrock	Calcium and magnesium from limestone or dolomite bedrock
Units of Measure	Expressed in logarithmic pH units	mEq/L, mg/L or ppm (meaning mg/L or ppm of calcium carbonate or bicarbonate equivalents)	mg/l or ppm
Impact on CEA operations	Minimal impact in container substrates if alkalinity and hardness are within acceptable range, but in hydroponics directly affects micronutrient solubility. Also affects activity of many agrichemicals	Increases pH of root substrate over time as carbonates accumulate, resulting in nutrient deficiencies	Scale deposits on plants and irrigation equipment. Clogged nozzles lead to plant stress.
Treatment	No treatment necessary if hardness and alkalinity within acceptable range for substrate production. High pH is adjusted with acid in hydroponic production.	Use of acidic fertilizer or acid injection into irrigation water. Reverse osmosis, deionization	Softening with KCl salts (not NaCl), reverse osmosis, deionization

Ion Exchange Resin Purification - Ion exchange entails passing water through a bed made of millions of charged resin beads. A bed of absorptive cation (positively charged) resin will exchange hydrogen ions for the positively charged ions in the solution, including sodium, calcium, magnesium, iron, and potassium. An anion (negatively charged) resin bed exchanges hydroxide ions for negatively charged particles in the solution such as chloride, sulfate, bicarbonate, and fluoride. For higher purity, the solution can be passed through a dual bed of ion exchange resins, first a cation resin and then an anion resin. Different qualities of water can be achieved according to the resin make-up, providing a host of treatment solutions too detailed for the scope of this guide. Of important note, ion exchange resin can remove boron ions effectively, and boron removal has proved a challenge for reverse osmosis technology.

Deionization - Passing water repeatedly through a **mixed resin bed** of positively and negatively charged resins produces water of a higher purity than is typically needed for CEA facilities, but often at a price several times higher than other methods. For this reason, operations seeking water of this purity typically treat with reverse osmosis and then "polish" the RO with this form of deionization at a greatly reduced operating cost compared to deionization alone.

Some horticulture water treatment experts point out that, since ion exchange resins create no reject water waste stream, this technology may be a viable alternative to treating recovered leachate in order to reach MLD or ZLD goals. However, like membrane technology, nutrients would be stripped out of the water, foregoing the cost savings on fertilizer that provide a suitable return on investment for the equipment.

Under most circumstances in CEA production, leachate needs to be discharged after repeated irrigation cycles due to accumulation of sodium or imbalances of plant nutrients. Though other technologies might be used to disinfect and purify leachate between irrigation cycles, deionization would be useful for removing nutrients that contribute to eutrophication of natural waterways (as well as other contaminants) before the leachate is discharged to the municipal sewer or environment.

Chlorine Disinfection - Chlorine is a widely used, typically low-cost water disinfectant for irrigation of plants in container substrates, and is effective on almost all microbial pathogens. It can be applied as chlorine gas, liquid (sodium hypochlorite), solid (calcium hypochlorite), or through electrochemical activation of a salt solution (typically potassium chloride). All forms react with water to form hypochlorous acid (free chlorine), which is effective at disinfecting zoospores of oomycetes such as *Pythium* at a concentration of 2 ppm of free chlorine with a required contact time of 5 minutes. Chlorine is best used with water sources that are pre-filtered for organic material and remain fairly uniform. Chlorine's effectiveness will vary with the water pH, alkalinity, temperature, and presence of biofilm, algae, and organic debris.[66] This can result in overapplication and plant damage if not carefully monitored. For example, a 2023 hydroponic study reported damage to lettuce from chlorine concentrations found in drinking water.[67] Chlorine from municipal source water is therefore often removed before use in hydroponic solutions, using a technology such as granular activated carbon. Chlorine use can also damage some crops and plant species used in constructed wetlands for bioremediation. One reason chlorine is not often used in CEA facilities is that free chlorine reacts with the ammoniacal-nitrogen in most water-soluble fertilizers to form chloramines, which are a less effective sanitizer than hypochlorous acid. As it is less effective in nutrient solutions and shown to damage crops in hydroponics, chlorine will not be covered in depth in this guide.

Chlorine Dioxide Disinfection - Although it is a chlorine compound, chlorine dioxide (ClO_2) does not form hypochlorous acid in contact with water. Instead, it is a dissolved gas that oxidizes pathogens directly upon contact. Importantly, ClO_2 is compatible with nutrient solutions used in fertigation. It is typically injected as a liquid concentrate from an on-site generator and readily diffuses in water through irrigation lines. More recently, tablets and water-soluble packets have been developed that can be dissolved directly in the solution. It can be used as a shock treatment between crop rotations at levels between 20-50 ppm, where it penetrates biofilm right down to the attachment points on hard surfaces, making it a very effective control agent for this purpose as well. It is less sensitive to pH and organic matter than chlorine. Furthermore, a generator can produce either a low dose for continuous injection or can create stock concentrations up to 3,000 ppm.

One advantage of ClO_2 generators is that one unit can serve multiple, independent irrigation systems prevalent at large facilities. Concentrates can be made by the generator and safely transported to other buildings where it is then diluted using standard irrigation dosing equipment. The expense of this technology is greater than other oxidizers, so some growers use it selectively on high-value crops or ones highly susceptible to disease. Some damage may occur to plants if ClO_2 is applied directly to foliage, such as in a mist propagation room.

Electrochemically Activated Water (ECA) - ECA-water is formed when a current is passed through a solution of potassium chloride or sodium chloride. As the salt water is electrolyzed, chlorine gas is formed, which dissolves in the liquid to form hypochlorous acid that is effective against bacteria, viruses, spores, mold, and fungi. It is non-toxic to humans and biodegradable. When higher voltages are applied, other oxidizing agents may form, including hydrogen peroxide, ozone, and hypochlorite. ECA-water is active against biofilm. A 2015 study comparing five disinfection technologies reported ECA-water most effective against fusarium and pythium.[68] ECA-water may also be stored for up to 48 hours before reverting to plain water. One downside is the creation of 2-10 ppm of active chlorine, which can be

66 Fisher, P., Huang, J., Looper, A., Minsk, D., Argo, B., Vetanovets, R., & Zheng, Y. (2008). Water treatment series, Part 5: Chlorine. Greenhouse Management. June 2008.

67 McGehee, C. S., & Raudales, R. E. (2023). Irrigation Sources with Chlorine Drinking Water Standard Limits Cause Phytotoxicity on 'Rex' Lettuce Grown in Hydroponic Systems. Horttechnology, 33(1), 125–130. https://doi.org/10.21273/horttech05091-22

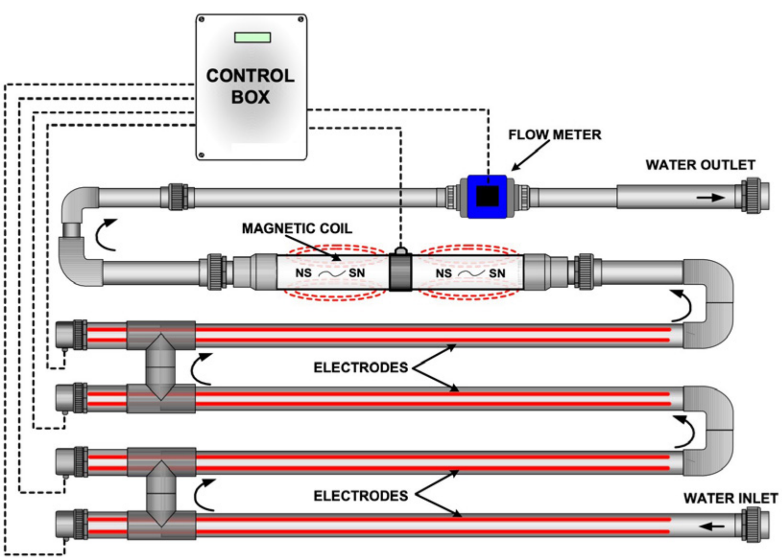
68 Europe PMC, Heungens, H., Clierinck, M., & Vissers, M. (2015). Efficacy of Novel Water Disinfection Techniques in Horticultural Nutrient Recycling. Communications in Agricultural and Applied Biological Sciences, 80(3), 539–550.

phytotoxic on lettuce in hydroponic production.[69]

Copper Ionization Disinfection - Copper ions attach to plant pathogens and disrupt their cell walls, killing the organisms at concentrations between 0.5 -1 ppm. Algae can be controlled at concentrations between 1-2 ppm. Copper sulfate has long been used as a fungicide, and modern treatments using ionization technology are even more effective. For ionization, copper electrodes are submerged into the water stream and electrified. Copper ions then displace from the electrodes and bond to pathogens in the water. Modern copper ionization systems have adjustable current settings that increase their effectiveness compared to earlier versions–the electrical current needs to be adjusted according to the varying flow rate and EC of the water. Copper ionization is widely used in applications such as mist irrigation of young plants to control algae on the substrate surface, rather than in recirculating hydroponic systems where there is potential for a phytotoxic increase in copper level.

To avoid phytotoxicity, copper concentration should be kept at fertilizer levels (typically below 0.5 ppm) in irrigation water. Environmental regulations should also be followed on copper concentration in discharge water.

Figure 25. Schematic of copper deionization unit.



Peroxyacetic Acid Disinfection - Peroxyacetic acid (PAA) is a combination of acetic acid and hydrogen peroxide. When injected into the water stream, free hydroxyl radicals oxidize cell membranes and penetrate into cell structures of algae, bacteria, and fungi. Due to the plant safety of their formulations, they are an excellent choice for sanitation of surfaces, continuous application at a low concentration, and even applied directly to plants as a fungicide or bactericide. Higher concentrations can be used as a shock application for plumbing between crop cycles, or for algae control in reservoirs. Roots of plants in hydroponic nutrient solutions are more sensitive to PAA than in container production, and lower rates are applied. Pre-filtering organic particulates is also important with PAA and other chemical treatments to reduce sanitizing demand for these contaminants and maximize effectiveness. A further advantage of these products is that they increase oxygen concentration of solutions as a byproduct of their mode of action.

Ultraviolet Light Disinfection - Ultraviolet light in the range of 240-280 nanometers (UV-C) disinfects by photo-oxidation. The high-energy wavelengths penetrate cell walls of algae, bacteria, and fungi and the protective protein coat of viruses to disrupt and destroy genetic information, either killing the organism or rendering it sterile. This technology has proven highly effective for control of pathogens and algae in irrigation water.

Ultraviolet light systems treat water as it flows through a steel tube containing the lamp, which is enclosed in a quartz sleeve. Water must have high clarity (low turbidity) for the wavelengths to penetrate and expose all the target organisms for disinfection. Therefore, pre-filtration for suspended solids or dyes is recommended. Iron chelates can also reduce UV transmission.

Because there is no residual effect downstream of the lamp, UV light disinfection is typically combined with ozone, peroxyacetic acid, or another residual treatment that will control biofilm. Ozone has been demonstrated to improve the effectiveness of UV treatments. According to cleanwater3.org, "[when] ultraviolet light is combined with ozone or peroxide, the resulting reaction forms more of the highly unstable and active hydroxyl radical, thereby increasing the sanitizing effect."[70] Routine maintenance of the UV lamps to remove deposits from the quartz sleeve is a best practice to maximize efficiency.

IMAGE: AQUA-HORT

[69] McGehee, C. S., & Raudales, R. E. (2023)

[70] Fisher (2009)

Ozone Disinfection - Like chlorine dioxide, ozone is applied as a gas dissolved in water, and has twice the oxidizing power of chlorine. It is produced on-site, usually with a corona discharge generator that applies electricity to oxygen (O_2) in order to convert some of the oxygen to ozone (O_3). That ozone is then injected into a pressurized tank using a venturi injector.[71] Ozone kills fungi, bacteria, oomycetes, and viruses that cause plant disease. It also provides an extra benefit to plant growth by increasing the oxygen concentration in the solution.

Commercial technologies have been developed that allow for continuous flow of aqueous ozone at levels safe for plants that control both plant pathogens and biofilm. University of Guelph research has reported ozonated water to be safe and effective on tomatoes in rockwool substrate at a rate of 3 ppm injected directly into the irrigation stream.[72] Additionally, ozone breaks down pesticides and plant growth regulators and is not affected by pH. If needed, high doses of O_3 may be actively removed with activated carbon filtration before reuse for irrigation.

A critical benefit of directly injecting ozone is it eliminates biofilm in irrigation lines and pipes at just 0.2 ppm, making it an important tool for CEA facilities.[73]

Disadvantages of ozone disinfection include the initial cost of installation and safety considerations. Though safe in solution, ozone in the air is dangerous for humans. As such, the areas where it is being generated must be monitored, with alarm and automatic generator shutdown triggers should a leak be detected. Plant safety must also be considered, as phytotoxicity has been observed on many species at ozone concentrations above 1.5 ppm.[74] Depending on the irrigation lines' contaminant levels, it

Figure 26. Schematic of ozone disinfection system.

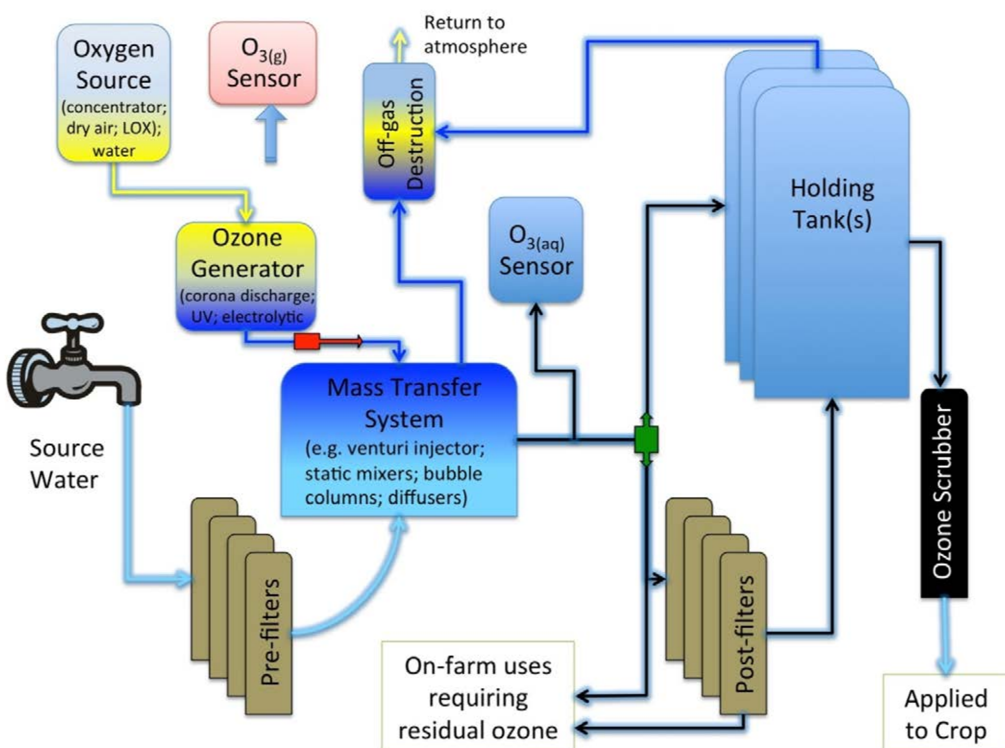


IMAGE: GRAHAM, 2012

[71] Graham, G. (2012). New Perspectives on the Maintenance of Aqueous Ozone Residuals in Greenhouse and Nursery Irrigation Solutions [PhD Dissertation]. University of Guelph.
[72] Graham, T. P., Zhang, P., Woyzbun, E., & Dixon, M. J. (2011). Response of hydroponic tomato to daily applications of aqueous ozone via drip irrigation. Scientia Horticulturae, 129(3), 464–471.
[73] West, J., Huber, A., & Carlow, C. (2018). Water Treatment Guide for Greenhouses & Nurseries. Agriculture and Agri-Food Canada.
[74] Graham, T. P., Zhang, P., Zheng, Y., & Dixon, M. J. (2009). Phytotoxicity of Aqueous Ozone on Five Container-grown Nursery Species. Hortscience, 44(3), 774–780.

often proves difficult to achieve an effective concentration at the terminal end without having to inject a concentration well above 1.5 ppm at the initial end of the line. Ozone level is typically measured at both ends, using common oxidative-reduction potential (ORP) sensors (ozone sensors can be too costly).

Another disadvantage is that ozone breaks down iron chelates and manganese chelates, requiring operators to reintroduce these micronutrients into the fertilizer. Organic matter also reduces the effectiveness of ozone. For these two reasons, it is important to both pre-filter (to remove organic matter) and post-filter (to remove iron deposits) when conducting an ozone treatment.

Ozone disinfection is often combined with UV disinfection or peroxyacetic acid disinfection to increase the sanitizing effect. The table below summarizes research findings on critical ozone levels and exposure times required to kill various pathogens.

Table 8. Critical level and exposure time for ozone disinfection of nine common biological contaminants of tap water.[75]

Microorganism	Critical Level (ppm)	Exposure Time (min)
Algae	.01-.05	N/A
Alternaria zinniae	0.7	16
Biofilm	0.2	30
Cucumber Green Mottle Virus	7.9	75
Fusarium oxysporum	1.6	2
Phytophthora capsici	1.5	23
Phytophthora cinnamomi	0.8	8
Pythium ultimum	1.2	2
Tobacco Mosaic Virus	100	30

[75] Modified from Zheng, Y. (2019). Ozonation. Greenhouse and Nursery Water Treatment Information System. University of Guelph. https://www.solutionozone.com/wp-content/uploads/2019/01/greenhousenurserywatertreatment_zheng-dunets-cayanan.pdf AND Grower Tool: Waterborne solutions. (2021). Retrieved May 6, 2023, from https://www.cleanwater3.org/gsearch.asp

Table 9. Comparison of varying physical water treatment systems.[76]

Physical Water Quality Treatment Systems														
Technology	Notes	Pre Treatment Required	Treatment Range						Reaction Time	Residual Effect	Reject Water Waste?	Footprint	Costs	
			Solids / organic material	Pathogens	Nutrients		Agri - chemicals	Controls Biofilm					Capital	Operating
					N	P								
Filtration - Coarse	Sand separator, Disc Filter, Belt Filter, Cartridge Filter	No, though may be multi-staged	✓						Instant			Small - Medium	$ - $$	$
Rapid Media Filters	Rapid Sand Filters, Greensand, Granulated Activated Carbon	Coarse filtration	✓			Media Dependent	Media Dependent		Instant			Small	$ - $$	$
Membrane Filtration - Microfiltration	Removes particles approx. 0.1 to 10 microns	Pre-filtration	✓						Instant			Medium	$$ - $$$	$$
Membrane Filtration - Ultrafiltration	Removes particles approx. 0.01 to 1 microns	Pre-filtration	✓	✓					Instant		+	Medium	$$ - $$$	$$
Membrane Filtration - Nanofiltration	Removes particles approx. 0.001 to .01 microns	Pre-filtration	✓	✓			✓		Instant		++	Medium	$$ - $$$	$$
Membrane Filtration - Reverse Osmosis	Removes particles approx. <0.0001 microns	Pre-filtration	✓	✓	✓	✓	✓		Instant		+++	Medium	$$ - $$$	$$
Membrane Filtration - High Efficiency Reverse Osmosis	Multiple membranes May retain portion of nutrients.	Pre-filtration	✓	✓	✓	✓	✓		Instant		+	Medium	$$$	$$
UV-C light	254 nm wavelength	Pre-filtration		✓					Instant			Small	$$$	$
Heat Pasteurization	85-95°C (185-203°F)			✓					Minutes			Medium	$$$	$$$

76 Modified from West, J., Huber, A., & Carlow, C. (2018). Water Treatment Guide for Greenhouses & Nurseries. Agriculture and Agri-Food Canada. and Fisher, P. (2020, February 18). Managing Water Quality and Biofilm for Indoor Production. Indoor Ag Science Cafe (episode 16). https://www.youtube.com/watch?v=O7wVuVLIEdk

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Table 10. Comparison of varying chemical water treatment systems.[77]

Chemical Water Quality Treatment Systems

Technology	Notes	Pre Treatment Required	Treatment Range						Reaction Time	Residual Effect*	Reject Water Waste?	Footprint	Costs	
			Solids / organic material	Pathogens	Nutrients		Agri - chemicals	Controls Biofilm					Capital	Operating
					N	P								
Chlorine	Caution with chloramine formation when using in fertigation solutions	Pre-filtration	✓	✓			Some	✓	Minutes	++		Small	$ - $$	$
Chlorine Dioxide		Pre-filtration	✓	✓			Some	✓	Minutes	++		Small	$ - $$$	$$ - $$$
Peroxyacetic acid	(PAA) is a combination of acetic acid and hydrogen peroxide	Pre-filtration	✓	✓			Some	✓	Minutes	++		Small	$	$$ - $$$
ECA	Chlorine 2-10 ppm may damage lettuce	Softening	✓	✓				✓	Minutes	+		Small		
Ozone		Pre-filtration	✓	✓			Some	✓	Minutes	+		Medium	$$$	$
Copper Ionization		Pre-filtration		✓					Hours	++		Small	$$$	$
Peroxyacetic acid + UV	Synergistic Effect	Pre-filtration	✓	✓			Some	✓	Minutes	++		Medium	$$$$	$$$ - $$$$
Peroxyacetic acid + Ozone	Synergistic Effect	Pre-filtration	✓	✓			Some	✓	MInutes	++		Medium	$$$$	$$$ - $$$$
Ozone + UV	Synergistic Effect	Pre-filtration	✓	✓			Some	✓	Minutes	+		Medium	$$$$$	$$
Deionization	Higher purity than typically needed	Pre-filtration and Reverse Osmosis to reduce cost	✓	✓	✓	✓	✓		Minutes		+++	Medium	$$$$$	$$$

*All technologies other than point treatments such as membrane filtration or UV have potential for phytotoxicity at high doses. Make sure to follow label and manufacturer recommendations on dose, monitoring, and maintenance.

77 Modified from West, J., Huber, A., & Carlow, C. (2018). Water Treatment Guide for Greenhouses & Nurseries. Agriculture and Agri-Food Canada. and Fisher, P. (2020, February 18). Managing Water Quality and Biofilm for Indoor Production. Indoor Ag Science Cafe (episode 16). https://www.youtube.com/watch?v=O7wVuVLIEdk

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Table 11. Comparison of varying biological water treatment systems.[78]

Biological Water Quality Treatment Systems

Technology	Notes	Pre Treatment Required	Treatment Range: Solids / organic material	Treatment Range: Pathogens	Treatment Range: Nutrients N	Treatment Range: Nutrients P	Treatment Range: Agri - chemicals	Treatment Range: Controls Biofilm	Reaction Time	Residual Effect	Reject Water Waste?	Footprint	Costs: Capital	Costs: Operating
Slow Sand Filters			✓	✓			*Possible*					Medium	$$	$
Constructed Wetlands			✓	Variable	✓	Variable	✓					Small - Large	$$-$$$	$
Floating Treatment Wetlands	Can be applied to existing stormwater ponds		✓	Variable	✓	Variable	✓					Small - Large	$-$$	$
Woodchip Bioreactors			✓	✓	✓	Some	*Likely*					Medium	$-$$	$
Hybrid Treatment Systems			✓	✓	✓	✓	*Likely*					Medium	$$-$$$	$

[78] Modified from West, J., Huber, A., & Carlow, C. (2018). Water Treatment Guide for Greenhouses & Nurseries. Agriculture and Agri-Food Canada. and Fisher, P. (2020, February 18). Managing Water Quality and Biofilm for Indoor Production. Indoor Ag Science Cafe (episode 16). https://www.youtube.com/watch?v=O7wVuVLIEdk

SECTION 07

Biological Remediation Systems

Many of the treatment technologies and practices discussed thus far fall under the broad categories of physical and chemical water treatment. Another important branch of water treatment to discuss is biological remediation. With the potential to remediate pesticides, sanitizers, and excess N and P in leach water, biological solutions typically consume very little energy. More recently, containerized versions of these technologies that may make them suitable for urban CEA operations have been commercialized.

Biological remediation or bioremediation is an engineered technology that combines natural physical, biological, and chemical processes to remove contaminants from the environment. A principal characteristic of bioremediation, which can be referred to as **green infrastructure**, is its aim to mimic the natural processes that occur within ecosystems. While there are many different designs and applications, listed below are examples of green infrastructure used within CEA.

- Constructed wetlands
- Bioretention systems (Vegetated Swales and Rain Gardens)
- Vegetated Buffers
- Slow Sand Filter
- Woodchip Bioreactors
- Land Application & Cascade Crops

These technologies and practices are important to water treatment in CEA due to their ability to remove the major pollutants in agricultural wastewater; excess nutrients

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> **Vegetated Buffers**

> **Constructed Wetlands**

> **Cascade Cropping Systems**

> **Floating Treatment Wetlands**

> **Hybrid Treatment Systems**

> **Woodchip Bioreactors**

> **Slow Sand Filters**

(nitrogen and phosphorus), pesticides, sediments, and even heavy metals with low energy input.[79] Additionally, these systems are crucial as they often deliver the final treatment of water before re-entering the ecosystem, and should be strongly considered for water circularity goals - only on a facility level but also on a watershed scale.

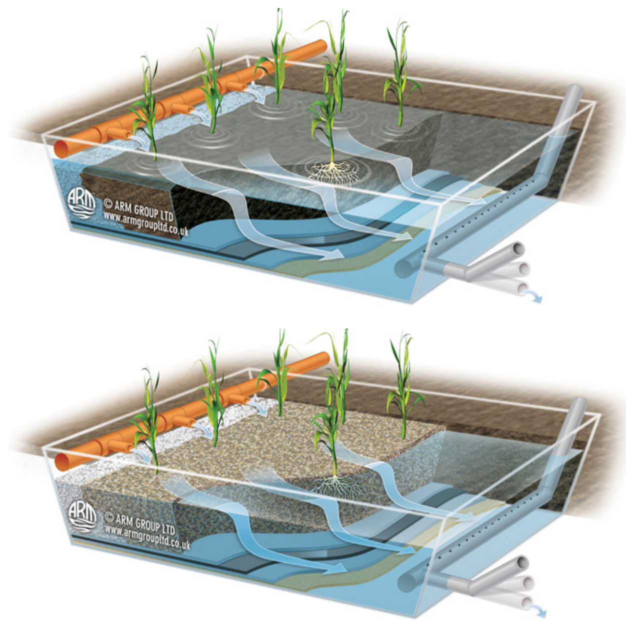
Vegetated Buffers - Below is an aerial photograph of a CEA facility with a river running through the property. A vegetated buffer of trees have been maintained along the river to help with agricultural runoff in this area.

Figure 27. Vegetated buffer system (highlighted) preventing runoff to nearby river.

Constructed Wetlands - One of the most widely used forms of green infrastructure for water treatment within the industry of CEA are constructed wetlands, more specifically **surface-flow and subsurface-flow constructed wetlands**. A simple difference between the two is a surface-flow constructed wetland is when the water pools above the surface like a natural wetland, while a subsurface-flow wetland consists of a basin filled with media (gravel, sand, or soil) where the water flows below the surface. Widely selected due to their many nutrient cycling pathways, constructed wetlands utilize a combination of many different mechanisms to clean water. Some examples of natural treatment processes that occur in constructed wetlands include:

- Physical: Sedimentation. The settling of suspended solids.
- Biological: Vegetative uptake. The uptake of pollutants into the biomass of wetland vegetation.
- Chemical: Sorption. The chemical bond of pollutants to wetlands sediment where the pollutant can be immobilized and can be available for vegetative uptake.

Figure 28. Surface flow constructed wetland (top and Sub-surface flow constructed wetland.



The primary benefit of using constructed wetlands for water treatment is its nutrient and pesticide removal success. Constructed wetlands have been shown to achieve high removal efficiency of nutrients; 50%-99% for nitrogen and 25%-98% for phosphorus. For pesticides, they can achieve a high removal efficiency of 84%-97% for organochlorines, strobilurin/strobin, organophosphates, and pyrethroids.[80] Additionally, wetland technology has demonstrated removal of two of the most prevalent heavy metals from plumbing and HVAC, copper (60%) and zinc (86%), along with lead, cadmium, aluminum, and manganese.[81,82] Relative to the other water treatment technologies, these are high removal rates for these key agricultural pollutants. Constructed wetlands can also be explored as an option for treating other CEA waste streams mentioned previously

IMAGE FROM LEFT: GOOGLE EARTH; AGRICULTURAL REQUISITES & MECHANIZATIONS LTD

79 West (2018)

80 White et al. (2011). Constructed wetlands: A how to guide for nurseries. — Nursery Crop Science. http://www.nurserycropscience.info/water/managing-runoff/extension-pubs/white-et-al.-2011.-constructed-wetlands-a-how-to-guide-for-nurseries/view

81 Gill, L., Ring, P., Casey, B. M., Higgins, N. M., & Johnston, P. A. (2017). Long term heavy metal removal by a constructed wetland treating rainfall runoff from a motorway. Science of the Total Environment, 601–602, 32–44.

82 Cheng, S., Grosse, W., Karrenbrock, F., & Thoennessen, M. (2002). Efficiency of constructed wetlands in decontamination of water polluted by heavy metals. Ecological Engineering, 18(3), 317–325.

like bleed-off and washdown water. The ions likely to be present in bleed-off water (Ca, Mg, Na, and K) will be present in high concentrations, but all should be able to be removed from water through treatment processes like the ones listed above. As for CEA waste streams including sanitizers and detergents like washdown water, treatment efficacy of constructed wetlands is less explored. However, there are present studies showing successful removal rates (82% and 39%-94%) of detergents in municipal and industrial wastewaters by subsurface flow constructed wetlands.[83,84]

Cascade Cropping Systems - More studies are present on the use of wastewater for irrigation of cascade crops. Cascade cropping systems refer to the practice of reusing water from waste streams in your facility for irrigation of other crops, either indoors or outdoors. Common examples of this are utilizing your drained fertigation water on field crops if your facility is sited near open field farming, or on potted commercial crops grown adjacent to the indoor operation. For example, cherry tomato may be grown using the leachate of more salt-sensitive round-fruit tomatoes.[85] There are also intriguing studies exploring the use of gray water for irrigation of ornamental species showing some promise for washdown water reuse. Care needs to be taken as many detergents contain high concentrations of chlorine which can cause phytotoxicity.[86] It is always important to understand what is in the drained water before reuse on other crops.

Another benefit includes low operating energy requirements. Pumping may be used in subsurface-flow constructed wetlands, but these systems are generally low-energy or passive. Planting trees or other plants for agricultural remediation also has carbon sequestration and atmospheric air quality benefits over time. For states with stormwater management regulations, a constructed wetland could be coupled to qualify for the site's stormwater requirements.

The largest implications of constructed wetlands are the large upfront cost and the land area required.

The cost is dependent on the size of the system, the amount of excavation, and the planting required. The system should be sized to accommodate the maximum volume of water expected to enter your system. The large land requirement often results in this technology only being viable in more rural sites.

Another important challenge to consider is the variability of pollutant removal success in constructed wetlands. Different wetland media have varying success in filtering and binding nutrients. Winters in cold climates have lower removal rates due to decreased biological activity at lower temperatures, and in certain instances these systems can become sources of pollutants. The open-air qualities of surface-flow systems and the outdoor nature of surface and subsurface systems make them susceptible to unwanted inputs like pathogens from vegetation or wildlife, particularly waterfowl. While the wetlands offer suitable purification for many recirculating systems, further filtering and disinfection will be necessary, especially for food crops.

As a wetland becomes more mature, the media also becomes more saturated and its phosphorus-binding capacity lessens, leading to lowered phosphorus removal. If paired with stormwater removal, increased rainfall events due to climate change can further lower your phosphorus binding capacity.87 Further, if not harvested, vegetation death can lead to organic matter buildup in the system, and the previously stored pollutants in plant biomass can leach back into the system. The labor and cost of required maintenance of plant harvesting, sediment removal, and media recharging remain challenges to overcome.

83 Karimi, B., Ehrampoush, M. H., & Jabary, H. (2014). Indicator pathogens, organic matter and LAS detergent removal from wastewater by constructed subsurface wetlands. Journal of Environmental Health Science & Engineering, 12

84 Hendr Ond For Domestic Wastewater Treatment. International Journal of Engineering Research & Technology. Vol.2 pg.3374-3382

85 Incrocci, L., Pardossi, A., Malorgio, F., Maggini, R. and Campiotti, C.A. (2003). CASCADE CROPPING SYSTEM FOR GREENHOUSE SOILLESS CULTURE. Acta Hortic. 609, 297-300

86 Cabrera, Raul I., James E. Altland, and Genhua Niu.(2018) "Assessing the Potential of Nontraditional Water Sources for Landscape Irrigation", HortTechnology hortte 28, 4): 436-444, accessed Mar 29, 2023,

87 Vermont Agency of Naturl Resources (2018). Vermont Guide to Stormwater Management for Homeowners and Small Businesses.

Figure 29. Constructed wetland root system (left) and top growth.

Floating Treatment Wetlands - An alternative and relatively new technology that avoids the high capital costs, construction, and maintenance of a traditional constructed wetland is retrofitting existing infrastructure, like a holding pond, with floating wetlands. Floating treatment wetlands are systems consisting of floating rafts that are planted with wetland vegetation. The roots grow through the raft and become suspended in the water, providing pollutant removal through uptake into the plant's biomass. Additionally, by providing surface area for microbial growth on the root zone, these rafts can offer further pollutant removal pathways.[88] In a study comparing removal rates of two leading brands' efficacy in treating agricultural wastewater, removal rates of 25%-40% for Total Nitrogen and 4%-48% for Total Phosphorus were achieved.[89] This technology is commercially available.

Hybrid Treatment Systems - Other green technologies can be used in tandem or in place of constructed wetlands to still achieve biological remediation in your CEA operation. A Hybrid Treatment System (HTS) is a relatively new adaptation of a subsurface wetland. Like the wetland, these systems consist of multiple cells filled with specific media, and the water flows through the cells under the surface. The difference is the media used to fill the cells can be customized to your facility's treatment goals.[90]

Woodchip Bioreactor - Hybrid treatment systems typically reserve one cell to fill with wood chips as media to form a woodchip bioreactor (see image to the right). When saturated with water to create anaerobic conditions (a lack of oxygen), the woodchips act as a carbon source to promote a **microbial community**. These denitrifying bacteria that make up the microbial community will remove the nitrate in your wastewater by converting it into nitrogen gas (N_2) that is then released into the atmosphere. Important in recirculating systems, these microbes have also been shown to have promising efficiency in removing fungal plant pathogens. The other cells in hybrid treatment systems can be filled with various mineral media that target pollutants your facility is looking to remove. Popular options are gravel and sand media (for their capabilities for filtering solids and removing phosphorus).

Figure 30. Woodchip bioreactor.[91]

IMAGE FROM TOP: STEVE BEEMAN; UVM, HURLEY LAB, DEPARTMENT OF PLANT AND SOIL

88 Spangler, J., Sample, D. J., Fox, L. J., Owen, J. E., & White, S. (2019). Floating treatment wetland aided nutrient removal from agricultural runoff using two wetland species. Ecological Engineering, 127, 468–479

89 Lynch, J., Fox, L.J., Owen, J. E., & Sample, D. J. (2015). Evaluation of commercial floating treatment wetland technologies for nutrient remediation of stormwater. Ecological Engineering, 75, 61–69.

90 West (2018)

91 Sarazen, J., Hurley, S., & Faulkner, J. (2023). Nitrogen and phosphorus removal in a bioretention cell experiment receiving agricultural runoff from a dairy farm production area during third and fourth years of operation. Journal of Environmental Quality, 52, 149– 160.

Hybrid treatment systems can be a better biological treatment solution for your facility by achieving similar advantages to constructed wetlands and gaining higher removal rates by specifically targeting key pollutants. They also perform slightly better in cold climates, have fewer land requirements, and require far less maintenance outside of regular monitoring. To overcome these systems' sizable land needs, containerized biological treatment technologies like slow sand filters can be considered.

Slow Sand Filters - SSFs are containerized systems in which water is dispersed over the top media (made up of medium-sized grains of sand less than 0.6 millimeters in diameter) and is treated as it flows vertically down through the sand. The sand provides physical filtration of suspended solids and pathogens while providing the conditions for the growth of microbial communities at the top of the sand media. The layer of the microbial community is referred to as "**schmutzdecke**" (German for "dirty skin" or "dirt layer") and consists of bacteria, algae, fungi, protozoa, and many more organisms that work together for further pathogen removal.[92] An added benefit is SSFs have a limited impact on nutrient concentrations, pH, and conductivity resulting in them being viable in recirculating systems.[93] Compared to the previously discussed technologies, the primary benefit of these systems is the ability to be containerized and, in certain situations, sited indoors.

Like the other systems, sizing SSFs for your facility is dependent on many factors like water quality, irrigation area, and how much of your water is recirculated, for example. To have a general idea of sizing, the Horticultural Development Council claims a nursery with 10,000 square meters (m^2) of irrigation area would require a minimum SSF surface area of $20m^2$ (assuming up to 35% of the water is recycled). Another general rule for sizing these systems is that every $1m^2$ (10.8 square feet) of surface area will result in 4 cubic meters (m^3)–or 1,080 gallons–of treated water per day.[94] Flow rate can be adjusted, but a faster flow rate can result in lowered removal rates. The Slow Sand Filter Sizing Tool is a free online resource to help with these calculations.

Slow sand filters can expand the range of CEA facilities able to use biological treatments in more urban environments and provide more consistent removal rates for operations in cold climates.

Figure 31. Slow sand filter schematic and during construction.

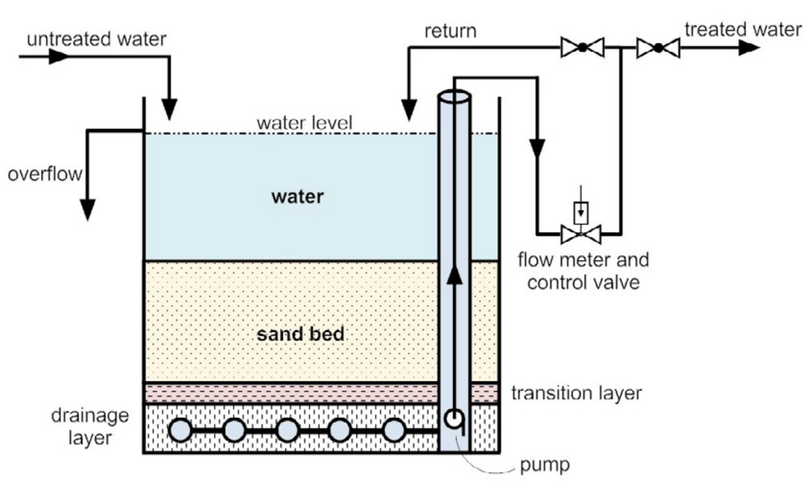


IMAGE: L. OKI

[92] Oki, L. R., Bodaghi, S., Lee, E. W. M., Haver, D., Pitton, B. J. L., Nackley, L. L., & Mathews, D. M. (2017). Elimination of Tobacco mosaic virus from irrigation runoff using slow sand filtration. Scientia Horticulturae, 217, 107–113.

[93] West (2018)

[94] Pettitt, T. & Hutchinson, D. (2004). Slow Sand Filtration: Installation, operation & maintenance. Horticulture Development Council.

SECTION

08

Prioritizing Water Remediation Decisions

This section is intended to guide decisions over selection and integration of technologies to *Reduce*, *Remediate* and *Recycle* water. Some facilities will only strive to *reduce* water consumption using methods detailed in earlier sections. Others will need to *reduce* consumption and *remediate* discharge water to comply with local, state, or federal mandates. Still others will move toward Minimum or Zero Liquid Discharge as they *reduce* consumption, *remediate* multiple water streams and *recycle* water within the operation, staying ahead of regulators and demonstrating their industry leadership with a climate-smart example. Typically, a successful water management design will be the result of an integration of the best available technology based on sound applications engineering.[95] The combination of technology may be unique to each facility and will require professional expertise in horticultural water treatment systems.

Designing Capacity of Water Treatment Systems - Measuring flow rates and testing water quality at different points in production is a best practice for understanding the kind of treatment and the capacity required. The system should be designed to manage the peak load rather than average load, otherwise plant health is at risk. Storing

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> Designing Capacity of Water Treatment Systems

> Decision Making for Facilities Remediating Discharge Water Only

> Decision Making for Facilities Remediating Multiple Water Streams

> Separation of Water Streams During Remediation

[95] Fisher, P. & cleanwater3.org. (2012). Designing a water treatment system, introduction and importance [Video]. YouTube.

treated water can reduce the cost of treatment equipment by allowing a slower flow rate through disinfection or purification, with the tradeoff being that storage tanks require a large amount of space and adequate transfer piping. Cleanwater3.org offers tools for calculating storage volumes.

Storage tanks also need monitoring and recirculating disinfection loops to keep the stagnant water from being recolonized with pathogens. These disinfection loops may use UV-C light, ozone, or peroxyacetic acid, and should be installed on clean water tanks as well as dirty water tanks.

Decision Making for Facilities Remediating Discharge Water Only - Many CEA facilities are facing new regulations on water discharged from their facility. For these operations, the answers are more straightforward but the volume of water may be high–if using 0.25 gallons/ft^2/day for irrigation with a 30% leach fraction without recirculation, the volume can be as much as 750 gallons/day for every 10,000 ft^2 of plant area.

Location is an important factor. A facility with extensive property may have the space for constructed wetland, cascade crops, woodchip bioreactors and buried slow sand filters. If the contaminant being remediated prior to discharge is pesticides or sanitizer, granulated active carbon filters may be used. These systems also can be set up in series, and typically require pre-filtration for best operation. They also need pressure gauges before and after the units to determine when backflushing may be required. Pre-filtration and reverse osmosis can be used to remove nitrogen and phosphorus ions from discharge water, though the ions will be concentrated in the reject water that must then be dealt with. Reject water can be hauled away at considerable cost. Evaporators can be used, but also at a high operational cost. Vacuum distillation has a significant purchase cost, but much lower operational cost.

Decision Making for Facilities Remediating Multiple Water Streams - For facilities remediating irrigation water, climate control water or process water, additional risks to plants, equipment, and even human health are increased. With so many choices for filtration, purification and disinfection, both mechanical and biological, where does one begin to decide how to remediate?

Much like water circularity has been broken to the three R's, it may be helpful to rank the priorities of remediation into four R's:

- **Restore water quality** for protection of plants.
- **Remove biofilm** for protection of people, plants, and equipment.
- **Reduce reject water** for protection of the environment.
- **Recover nutrients** to protect the operation's bottom line.

This ranking of priorities is a modification of principles described in the *Ball Redbook: Greenhouse Structures, Equipment, and Technology*. Combined with the tables and charts provided below, the selection of equipment begins to fall in place as one applies these priorities to their own facility and remediation goals. We also strongly recommend the reader use the 'Waterborne Solutions' tool and other resources for decision-making on the cleanwater3.org website.

- **Restore Water Quality for the Protection of Plants** - Remediated water reused for irrigation must be disinfected prior to application, otherwise plant disease outbreaks may occur. A 2014 report details the effectiveness of various physical, chemical, and biological water treatment systems in controlling waterborne microbes that cause disease.[96] However, all chemical disinfectants, including dissolved ozone, may lead to plant damage if overapplied, or if toxic residuals or chemical by-products are created. Nutrients not taken up by plant roots also can concentrate in recirculated systems, leading to phytotoxicity. Sodium and chlorine from fertilizer salts are among the greatest risks to plant health from concentration.

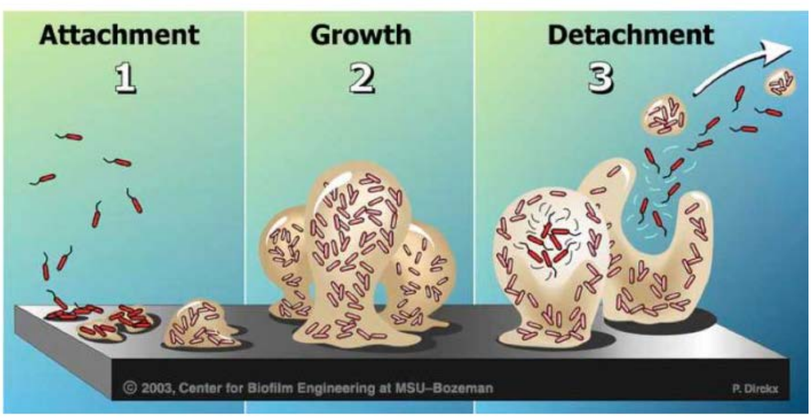
  According to the *Ball Redbook*, "Rule number 1 when designing an irrigation water treatment system is to do no harm to the plants, so start at the plant first and work your way back to the water source." This provides the key to where to begin the decision-

[96] Raudales, R. E., Parke, J. L., Guy, C. L., & Fisher, P. B. (2014). Control of waterborne microbes in irrigation: A review. Agricultural Water Management, 143, 9–28.

making process. Once a set of water quality restoration technologies is selected to protect plants and to remove biofilm, then it is quite likely that it will also adequately treat the source water. The opposite is not true, as many common source water treatments do not protect plants and remove biofilm, which is why we begin here.

- **Remove Biofilm for Protection of People, Plants, and Equipment** - What exactly is biofilm? It is the gunk in your pipes, the plaque on your teeth, the slime on submerged rocks in a stream. You are likely to find biofilm anywhere where there is moisture, nutrients, and a surface. Floating bacteria attach to a surface, such as an irrigation pipe, within minutes and begin to exude sugars, nucleic acids and proteins to hold it in place. This matrix protects the bacteria and also becomes a host to other microorganisms including fungi, algae, yeasts, protozoa, as well as debris. The bacteria grows and releases more floating cells that start the cycle all over again downstream.

Figure 32. Biofilm development stages.



Although discovered centuries ago, much has been learned of biofilms in the last decade which reveals it to be one of the highest priorities in water treatment. The Montana State University Center for Biofilm Engineering provides comprehensive resources.

In CEA facilities, biofilms can become hosts of both plant and human pathogens. According to a 2005 scientific review, "Plant pathogens detected from water resources include 17 species of *Phytophthora*, 26 of *Pythium*, 27 genera of fungi, 8 species of bacteria, 10 viruses, and 13 species of plant parasitic nematodes."[97] Biofilms form in irrigation lines, tanks, and inside equipment including membranes of water purification equipment. In addition to harboring diseases, biofilm can reduce flow rates and clog nozzles and drip emitters.

Because biofilm is protected by a matrix, it survives exposure to disinfectants that can easily control the floating bacteria. Many disinfectants can kill biofilms, but the required dose is harmful to plants. Ornamental plant nurseries and greenhouses often have seasonal cycles that lend themselves to "shock treatment" applications in periods when plants are not present. Typically, this practice is unsuitable for CEA facilities using perpetual planting cycles.

Only four technologies can effectively remove and prevent biofilm at levels that do not harm plants: ozone, ECA-water, peroxyacetic acid, and chlorine dioxide. Therefore, it should be considered a best practice for food-producing CEA facilities to use one or more of these (along with the required associated pre-filtering). As stated earlier, ozone and peroxyacetic acid used together synergize disinfection. This may clarify decision-making for water disinfection.

- **Reduce Reject Water for Protection of the Environment** - As described earlier, reject water is the brine of concentrated nutrients and contaminants created by membrane filtration and the water used to backflush rapid sand and cartridge filters. Treating reject water, whether on-site or at a municipal treatment facility, is often energy-intensive. A best practice is to minimize the use of standard reverse osmosis purification systems. Facilities hoping to achieve MLD or ZLD may still need to use membrane filtration to remove contaminant ions of sodium and chloride from their primary water source, but operators can reduce reject water by nearly two-thirds by using rainwater or condensate as pure water sources.

IMAGE: CENTER FOR BIOFILM ENGINEERING, MONTANA STATE UNIVERSITY

97 Hong, C., & Moorman, G. W. (2005). Plant Pathogens in Irrigation Water: Challenges and Opportunities. Critical Reviews in Plant Sciences, 24(3), 189–208.

- **Recover Nutrients to Protect the Bottom Line** - Effectively treating water in your facility will likely not add any value to your product, only reduce risk. Without added value that could improve margins, how can a CEA facility afford the installation and operational costs of multiple technologies? Water savings will not be enough as the cost of municipal water is often held artificially low–one of many incentives localities use to attract businesses to build in their tax district.

  One answer may be fertilizer cost savings of recirculating nutrient solution. Growers report a two-year ROI on remediating and reusing fertigation solutions (and it should be noted that this report was prior to the doubling of fertilizer prices that occurred in 2021-2022).[98,99] A report on typical costs for a Dutch greenhouse in 2016 indicated that fertilizer cost savings helped recover the investment on purification, disinfection, and storage tanks, indicating, "[from] a purely financial perspective it therefore makes sense to operate a closed hydroponic system within your greenhouse."[100] Design your water purification to retain the nutrients not absorbed by plants rather than strip them out.

  Rebalancing nutrients is done following leachate disinfection. Rebalancing methods vary according to how variable the crop's nutrient uptake pattern is and the level of technology the facility has installed. At its simplest, the crop has a predictable uptake pattern. The leachate is blended with a percentage of freshwater and then used in a fertilizer injector to "top off" nutrients. The fertilizer formulation used in this rebalancing has a constant EC and ratio of nutrients. This **static blending** system can be done without sophisticated fertigation controls.

  The next level of control requires a computerized controller and sensors that blend in fresh water based on EC of the leachate, rather than a static percentage of the final solution. Topping off occurs with a fixed nutrient formulation, but EC is better controlled in the rebalanced solution. An excellent paper on this mass balance approach was published in 2022 by Utah State University.[101]

  EC is only a general measure of dissolved nutrients and does not accurately measure the concentration and ratios of specific nutrients. For fully optimized production using recirculated fertigation solutions, lab testing is performed on the leachate. Based on these measured nutrient levels, specialized fertilizer injectors with heads for each individual nutrient are employed to rebalance the nutrient concentration and ratios. This method accounts for the variable uptake that occurs between nutrients and across crop stages. Samples are taken for laboratory testing typically every week or two, although some growers test daily.

  Some operations have effectively found a hybrid between static blend and ion-specific rebalancing: having several stock concentrates with unique formulations that provide more tools for rebalancing.

  Research is being conducted at commercial scale using ion-specific sensors and injection heads to continuously measure each nutrient in the leachate, compare those values to the desired ranges, then adjust the injector heads for each nutrient as needed *in real time*. This would theoretically improve yield by reducing nutrient imbalances that occur between samplings (which can be as infrequent as every 14 days). Results so far have shown ion-specific sensing accuracy of 92% compared to private laboratory nutrient analysis, but further software programming is required to adjust the individual nutrients in response.[102]

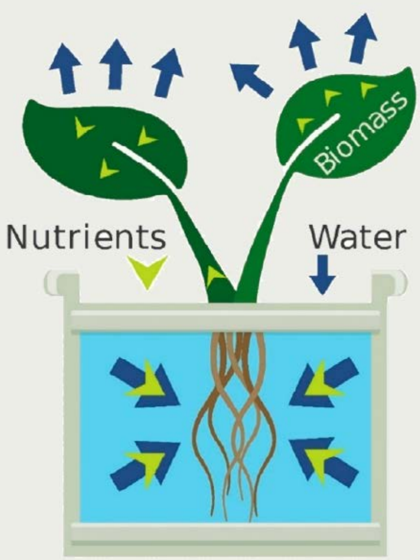
  No matter what technique is used to recharge nutrients into the solution, water treatment experts recommend a design to keep concentrated nutrients from being added close to the oxidizing disinfectant dosing point to minimize interaction.

98 Zylstra (2021)
99 YCharts.com (2023). Fertilizers Price Index. Retrieved May 6, 2023, from https://ycharts.com/indicators/fertilizers_index_world_bank
100 Lee (2016)
101 Langenfeld, N., Pinto, D., Faust, J. E., Heins, R. D., & Bugbee, B. (2022). Principles of Nutrient and Water Management for Indoor Agriculture. Sustainability, 14(16).
102 Abbenhuijs, R. (2022). Update 4 Demonstratie ionspecifiek telen - Celine meting - Glastuinbouw Waterproof. Glastuinbouw Waterproof.

Separation of Water Streams During Remediation- Though it is tempting to simplify the water remediation process by directing all liquids from the facility into a massive tank or pond to be purified and disinfected, this approach is neither practical nor economical. Industry experts recommend only remediating water as much as it needs for the given purpose. By diluting a heavily contaminated source, such as reject water, with a clean source, like condensate, you are increasing the volume that has to be remediated with more sophisticated equipment. Increasing the volume means larger capacity equipment and storage requirements that in turn come with increased energy and maintenance costs.

Recommended best practices for separating or combining multiple water streams include:

- Separate any water intended for irrigation from washdown water, reject water, or blow-down/ flush water.
- Irrigation leachate can be combined with rainwater and/or condensate for the disinfection step to save on the cost of multiple pieces of equipment. However, the rainwater or condensate must be treated for particulates, excess metals, and other inorganic contaminants before this combination.
- To avoid unnecessary waste, rainwater and condensate–which are nearly pure–should not be combined with any water that is going to be purified/disinfected by membrane filtration that produces reject water.
- Sanitation wash water, blowdown water from boilers and cooling towers, and bleed-off water from evaporative pad reservoirs will most likely be combined prior to treatment for final discharge, evaporation, or vacuum distillation.
- Separate conveyance and wash water for produce (flumes, hydro-coolers, bar sprayers, dump tanks, polishers, barrel washers, etc.) from other water types and follow FDA regulations for remediation and re-use. In some cases, potable water for final rinses can be re-used for earlier rinse steps, such as dump tanks.[103]
- Compost drainage water should be reapplied to the compost and kept separate from nearby surface water.



Significant water savings are possible by recycling irrigation water. In a highly cited paper, Bugbee (2004)[104] described a **mass balance** approach to nutrient management that does not require leaching or discarding nutrient solutions. Langenfeld et al. (2022) did a comprehensive update. The authors have maintained deep-flow hydroponic nutrient solutions for over a year without discarding the solution. This approach does not require monitoring individual ions in solution but rather calculates nutrient requirements based on mass balance. The principles apply to both liquid hydroponics and fertigation of soil-less media.

[103] Center for Food Safety and Applied Nutrition. (1998). Guidance for Industry: Guide to Minimize Microbial Food Safety Hazards for Fresh Fruits and Vegetables. U.S. Food And Drug Administration.

[104] Bugbee, B. (2004). Nutrient Management in Recirculating Hydroponic Culture. In: Proceedings of the South Pacific Soilless Culture Conference. M. Nichols, (ed.). Acta Hort 648: 99-112.

Table 12. Suggested Water Treatment Options Prior to Use for Irrigation

Suggested Water Treatment Options Prior to Use for Irrigation

Dependent Upon Water Chemistry, Capacity, Final Use, Cost, and Local, State and Federal Regulations

	Filtration - Coarse	Rapid Media Filters	pH Adjustment	Demineralization (softening)	Membrane Filtration - Microfiltration	Membrane Filtration - Ultrafiltration	Membrane Filtration - Nanofiltration	Membrane Filtration - Reverse Osmosis	Membrane Filtration - High Efficiency Reverse Osmosis	UV-C light	Heat Pasteurization	Chlorine or Bromine	Chlorine Dioxide	Peroxyacetic acid	Ozone	Copper Ionization	ECA-water	Peroxyacetic acid + UV	Peroxyacetic acid + Ozone	Ozone + UV	Deionization	Electrodialysis	Evaporator	Vacuum Distillation	Slow Sand Filters	Constructed Wetlands	Floating Treatment Wetlands	Woodchip Bioreactors	Hybrid Treatment Systems	Cascade crop
Source Water	✓	✓	✓	✓			✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓			✓	✓	✓	✓	✓	✓
Irrigation Leachate	✓	✓	✓							✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓		✓				some	some	some	some	some
Rainwater	✓	✓								✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓					✓	✓	✓	✓	✓	✓
Condensate		✓								✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓						some	some	some	some	
Produce Washdown Water*	✓	✓								✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓										
Produce Conveyance Water*	✓	✓								✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓										

Table 13. Suggested Water Treatment Options Prior to Discharge

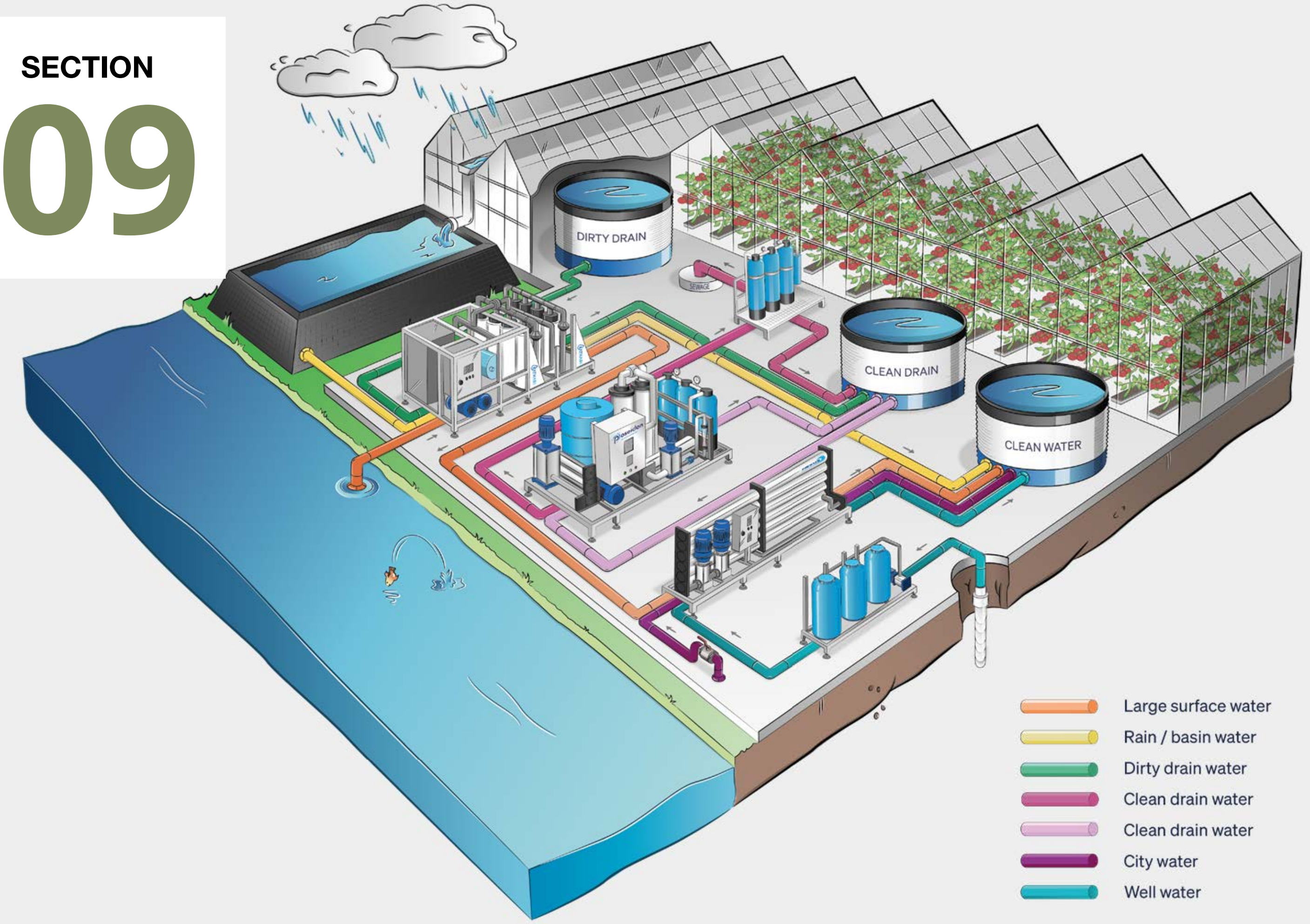
Suggested Water Treatment Options Prior to Discharge

Dependent Upon Water Chemistry, Capacity, Final Use, Cost, and Local, State and Federal Regulations

	Filtration - Coarse	Rapid Media Filters	pH Adjustment	Demineralization (softening)	Membrane Filtration - Microfiltration	Membrane Filtration - Ultrafiltration	Membrane Filtration - Nanofiltration	Membrane Filtration - Reverse Osmosis	Membrane Filtration - High Efficiency Reverse Osmosis	UV-C light	Heat Pasteurization	Chlorine or Bromine	Chlorine Dioxide	Peroxyacetic acid	Ozone	Copper Ionization	ECA-water	Peroxyacetic acid + UV	Peroxyacetic acid + Ozone	Ozone + UV	Deionization	Electrodialysis	Evaporator	Vacuum Distillation	Slow Sand Filters	Constructed Wetlands	Floating Treatment Wetlands	Woodchip Bioreactors	Hybrid Treatment Systems	Cascade crop
Fouled Irrigation Leachate, Produce Washdown or Conveyance Water	✓	✓	✓	✓	✓																		✓	✓	✓	✓	✓	✓	✓	✓
Sanitation Washdown Water		✓	✓	✓																			✓	✓		✓				✓
Reject Water		✓	✓	✓																			✓	✓						
Evaporative Cooling bleed-off		✓	✓	✓																			✓	✓		✓	✓		✓	
Cooling Tower Blowdown		✓	✓	✓																			✓	✓						

SECTION

09



Remediating Multiple Water Streams: Toward Minimum Liquid Discharge

In this section we will introduce schematics developed with the expertise of the RII's Water Circularity Working Group of over thirty experts from industry, academia and government. A strong caution is warranted here: <u>There is no best treatment or technology, only one best solution for each given facility</u>. The best solution is completely dependent on chemistry, biology and physical make-up of the water, as well as its intended use.

Figure 33. Rendering of a greenhouse facility with three water sources: rainwater (yellow pipes), surface water supply (orange), and well water (blue), and remediation equipment to treat irrigation leachate, or drain.

SECTION 9 CONTENTS:

> Open System Schematic
> Minimum Liquid Discharge System Schematic
> Zero Liquid Discharge System Schematic

IMAGE: VAN DER ENDE GROUP

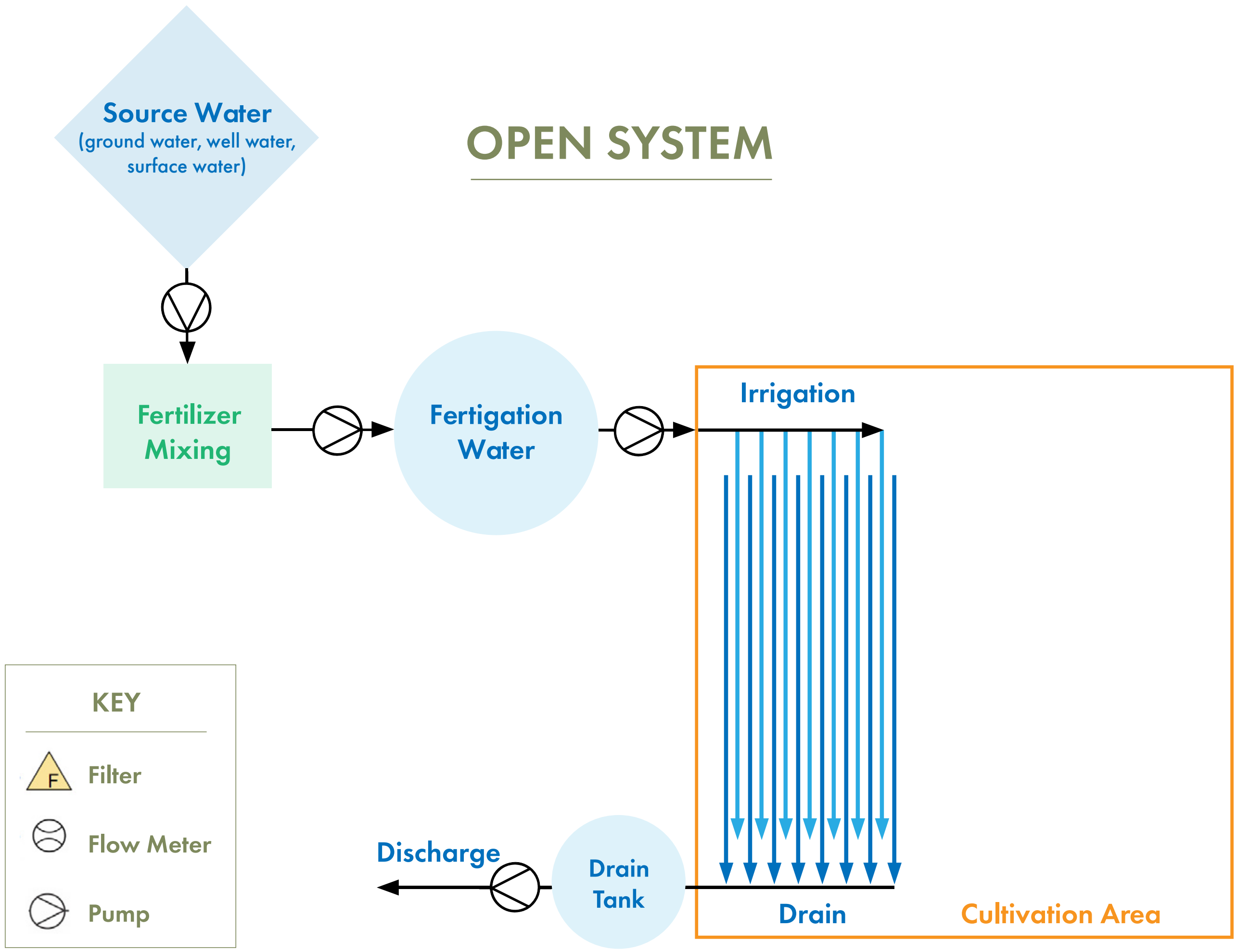


Figure 34. Schematic of a facility with an open system with no water recapture or remediation.[105]

Open System - The first schematic is of a standard CEA facility without remediation and water recycling. At the Fertilizer Mixing Unit, primary water supply is mixed with fertilizer formulations and pH adjusted before being stored in a Fertigation Water Tank. This fertigation solution is pumped into the cultivation area, used once and then discharged from a Drain Tank either to a municipal sanitary sewer or on-site septic field. If located in a more rural location, the discharge may be captured in an evaporation pond along with stormwater. It may also be applied to land or outdoor crops.

Minimum Liquid Discharge System - The second schematic represents a closed system with Minimum Liquid Discharge. In keeping with our ranked priorities for remediation, fertigation water is re-used, if suitable, or directed to the remediation loop, beginning with a Drain Tank, particulate filter, and Dirty Leachate Tank. From here it is filtered again and pumped to a Disinfection Unit. Alternatively, if testing indicates it is no longer suitable for use, it goes to a Discharge Option. The disinfection process will preferably be a technology that controls biofilm, such as ozone, ECA-water, peroxyacetic acid, and/or chlorine dioxide, instead of a technology that creates reject water waste (e.g. membrane filtration).

105 Modified from Van Der Salm, C., Voogt, W., Beerling, E., Van Ruijven, J., & Van Os, E. (2020). Minimising emissions to water bodies from NW European greenhouses; with focus on Dutch vegetable cultivation. Agricultural Water Management, 242, 106398.

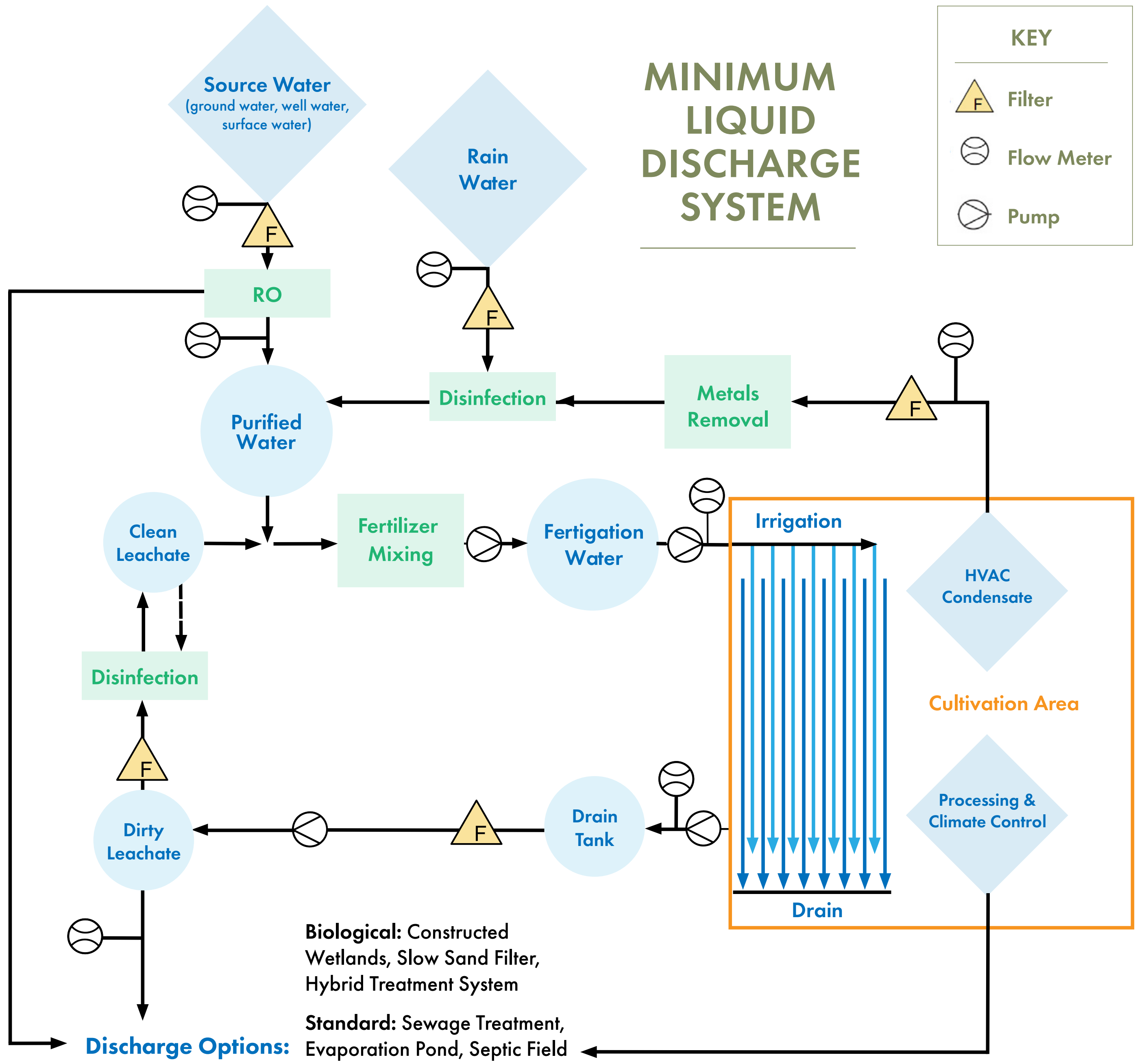


Figure 35. Schematic of a Minimum Liquid Discharge facility with rainwater recapture, condensate recapture, and both standard and biological discharge options.[106]

The disinfected water is then stored in a Clean Leachate Tank, where it is mixed with water from the Purified Water tank that is very low in sodium and chloride. The source of the purified water is from one or more of three possible sources:

1. Primary water pre-filtered and treated by RO.
2. Condensate that has been pre-filtered, treated to remove heavy metals and other inorganic contaminants, followed by disinfection of microorganisms.
3. Disinfected rainwater.

Clean leachate is mixed with this purified water at 25%-50% of final volume, or the mixing is conducted until a desired EC is reached (typically 0.5-0.8 milliSiemens/cm), before being recharged with nutrients to the proper level by the Fertilizer Mixing Unit.

[106] Modified from Van Der Salm, et al. (2020).

It is critical to keep water stored in tanks from stagnating and being reinfected in periods of low irrigation demand. A disinfection loop (designated as a dashed arrow from the Clean Leachate Tank back to the Disinfection Unit) is required to continue disinfecting this remediated solution. To save the cost of having multiple disinfection units, or to supplement with multiple disinfection technologies, the loop may also circulate the water back through a central disinfection unit(s) between the Dirty Leach Tank and the Clean Leach Tank (as indicated on the schematic). Some experts advise looping it back to the Dirty Leach Tank. However it is accomplished, it is vital that stored water be continuously disinfected and agitated. These disinfection loops may use UV-C light, ozone, or peroxyacetic acid, and <u>should be installed on clean water tanks as well as dirty water tanks</u>.

Figure 36. Water tank with UV light disinfection loop (left) and UV loop on underground rainwater tank.

Like the open system, the discharge option may be to a municipal sanitary sewer, on-site septic, or evaporation ponds. Granular Activated Carbon filtration may be used to remove pesticide residues. A biological remediation system also might be used, or the water could be applied to a cascade crop either inside or outside of the facility. All of what is described above must be done according to local and state regulations.

It should be noted that in some cases, the quality of the discharge water is demonstrably equal to–or even better than–the quality of the primary water coming into the facility. This might be an alternative way of defining MLD, in that it represents minimum *solids* discharged in the liquid (MSDL).

This MLD or MSDL system accomplishes the remediation priorities to **Restore water quality** for protection of plants; **Remove biofilm** for protection of people, plants, and equipment; **Reduce reject water** for protection of the environment; and **Recover nutrients** to protect the bottom line.

Though a vast improvement in water circularity over an open system, some limitations still arise. The expense of purchasing and operating the equipment is high, even if significantly offset over time by reduced fertilizer costs. Also, if the majority of the purified water used for remixing with the clean leachate comes from a source treated by reverse osmosis, a great deal of reject water will be created. Finally, there is no remediation plan for water streams other than fertigation solution.

Zero Liquid Discharge System - The last schematic depicts a Zero Liquid Discharge facility. ZLDs provide the water circularity of an MLD facility while remediating all water streams resulting from cultivation activities. In this scenario, discharged leachate, climate control water, and process water is discharged in one of three ways:

1. Evaporation;
2. Vacuum distillation;
3. Bioremediation and recycling within the interior of the building.

No water is discharged from a ZLD cultivation facility (other than black water). Examples of recirculated water streams that are not cultivation-related are sanitary washdown water and blow-down water from cooling towers and evaporative systems.

<u>The energy consumption and cost of evaporators are of great concern and call into question the validity of this approach if the discharge volume is high</u>. Vacuum distillation also represents a significant capital expenditure however, depending on local discharge regulations, may be a viable solution for dealing with otherwise difficult waste streams such as leachate with high EC and washdown water.

IMAGE LEFT: SILVER BULLET

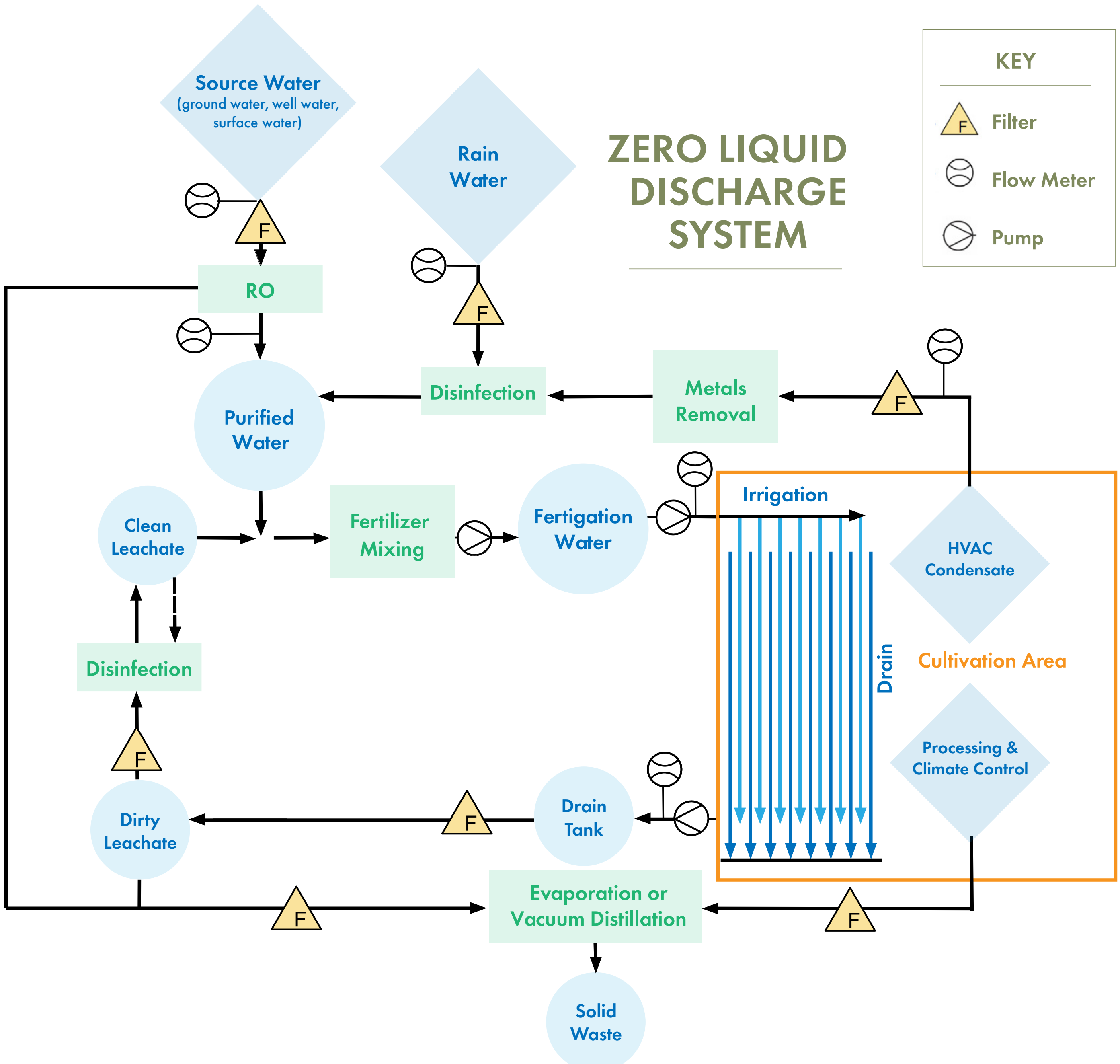


Figure 37. Schematic of a Zero Liquid Discharge facility with rainwater recapture, condensate recapture, and evaporation or vacuum distillation of liquid waste into solid or slurry.[107]

In the case of greenhouses with evaporative cooling pads, a high volume of bleed-off water from these systems is generated during warm periods. Reducing this bleed waste would greatly reduce the water volume needed for evaporation. Reducing sanitary washdown water can be achieved as described in earlier sections of this guide. Bioremediation systems constructed indoors would make ZLD more feasible, as leaks into the environment would be far less likely. The indoor environment also would avoid cold seasons that slow the biological processes, but those advantages are potentially offset by the cost of heating dedicated space.

107 Modified from Van Der Salm, et al. (2020).

Conclusions of Wageningen study

"During four years ZLD was investigated for cucumber (2014, 2017) and sweet pepper (2015, 2016). The primary goal was to reuse all drain water, while maintaining a similar yield and quality as in the traditional growing method with regular discharges." Some of the conclusions:

- Production and quality were not negatively influenced by full recirculation
- Mgmt of flows more challenging than technical issues
- Start with nearly sodium-free water Note: rainwater was a primary source
- Stone wool or coir substrate could be used, with specific mgmt techniques
- Weekly analysis of solution required
- Careful attention to end of production, water in slabs and storage tanks, nitrate replaced by chloride[108]

Figure 38. Zero Liquid Discharge closed loop system for treatment of RO reject, HVAC condensate, irrigation leachate, and municipal water (left) and pumps, filters, and underground reservoirs in a large greenhouse range.

IMAGE TOP: BEAR AG

[108] Zero liquid discharge in soilless greenhouse horticulture: solutions to save water and the environment while ensuring an optimal production" E.A. van Os, et al., 2020

SECTION

10

Designing Water Technical Areas

Careful planning is required to determine the space needed for water treatment and storage, safe access to equipment and the size of building doorways and corridors to bring in equipment and palleted supplies.

Determine the Volume To Be Stored - Calculating the volume of water stored is a cost-benefit analysis weighing risk of supply interruption against the cost of equipment and space to house the storage. Many industry experts suggest storing as little water as possible due to the expense and space required, as well as the challenge of keeping organisms from colonizing the tanks. Suggested capacities range from 0.75 to 5.0 days' worth of water that should be stored for irrigation, with one summer day's worth being the most common amount. If remediated water is also stored on-site, that will provide some buffer against supply interruption.

Keep in mind the trade-offs between how quickly water can be treated and the amount of water storage needed. The faster that treatment rate is, the quicker the tank can be refilled, so less storage volume is required. However, increasing the capacity of the treatment system to cycle

SECTION 10 CONTENTS:

> **Determine the Volume To Be Stored**

> **Plan the Water Technical Areas**

> **Treatment of Water While in Storage**

> **Pumps and Metering for Water Storage and Treatment**

faster increases the equipment cost. Having more storage volume could thereby save equipment costs. Also, using multiple storage tanks may also serve as a containment strategy in case of mechanical error or contamination. However, many operations simply don't have the room for large storage tanks and need to purchase higher-capacity treatment equipment.

Figure 39. Water storage tanks being installed in an indoor farm.

Figure 40. Rendering of nutrient dosing system with acidification and ozone disinfection. Nutrient dosing systems, day tanks, and associated plumbing.

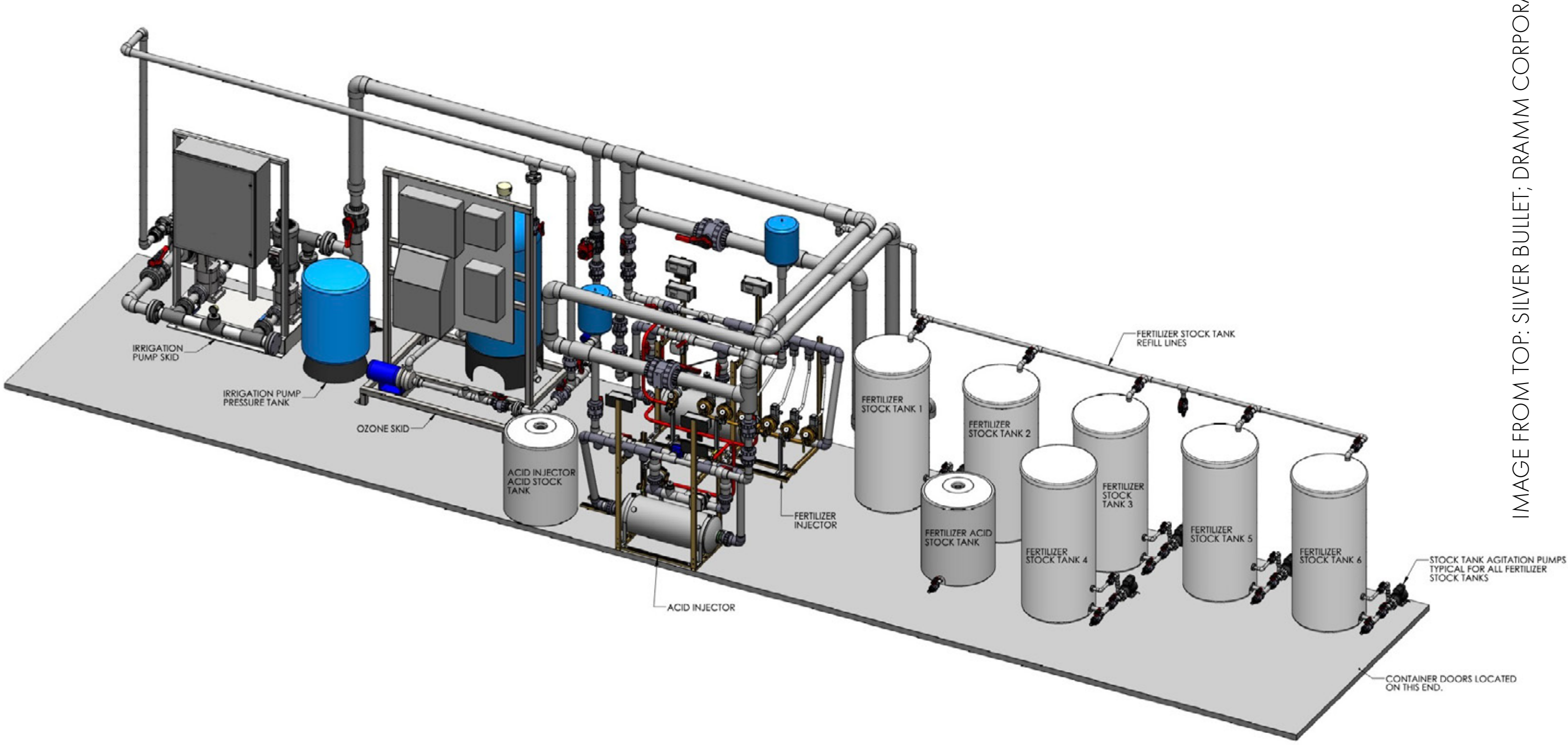


IMAGE FROM TOP: SILVER BULLET; DRAMM CORPORATION

Plan the Water Technical Areas - Careful consideration is required when determining where water will be stored and treated. Room sizing will depend on what, if any, water streams will be stored and if so, whether storage will be indoors or outside. For example, rainwater is often stored outdoors in wide, covered tanks, while Water Technical Areas can have high ceilings to accommodate tall water tanks to maximize volume stored by floor area. Other hardware considerations include the potential numerous tanks for nutrient solutions, fertigation equipment, water treatment equipment, and associated plumbing.

Often overlooked in the design is proper and safe access to all areas and equipment. All equipment should have a minimum of one yard (roughly one meter) of clearance to allow employees to safely work and egress. Large overhead doors may be required to replace tanks and other large equipment in addition to clearing a path in and out of the building to move these items. Seismic and structural codes and regulatory considerations need to be followed due to the excessive weight of stored water. The decision to use flat-bottom tanks or cone-shaped tanks with steel supports also can influence floor capacity.

Figure 41. Schematic representation of a water technical room

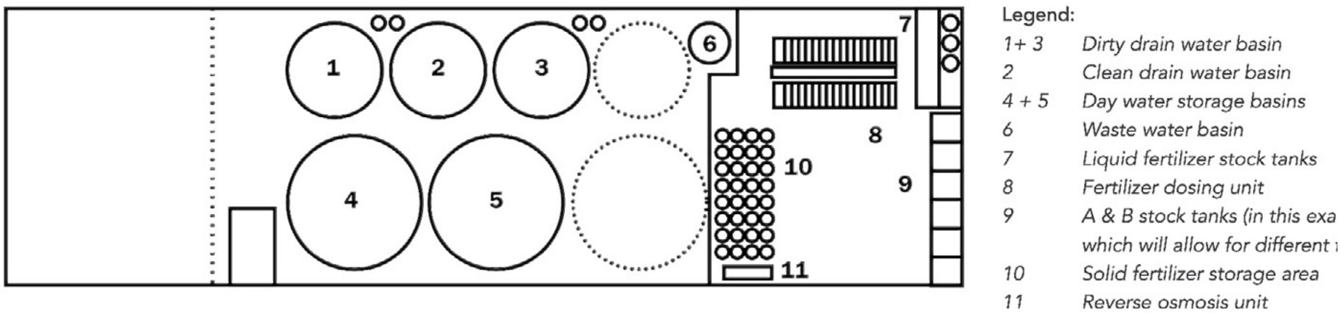


Figure 42. Water technical area at an indoor farm.

Treatment of Water While in Storage - Monitoring and controlling water quality while it sits in storage tanks is required to avoid contamination with dirt or biological organisms, and to curtail reduced oxygen concentrations. Tanks should be covered to prevent physical contaminants such as dust or airborne organisms from contaminating the water. Care also should be taken to maintain room temperature in cold climates and to avoid tanks being exposed to direct sunlight. Solution inside the tanks should be agitated or bubbled with an air supply to prevent hypoxia. A simple recirculation loop with a built-in ultraviolet germicidal light can both agitate and keep water disinfected while in storage. Oxygen concentration and temperature should be monitored and set to trigger alarms if levels leave a set range. Monitoring of pH and total dissolved solids is required for proper pH and nutrient mixing during treatment.

Pumps and Metering for Water Storage and Treatment - A best practice for resource efficiency is to correctly size and install **variable frequency drive (VFD)** pumps, or modulating pumps, to your systems. Utility companies are more familiar with pumps than specialized irrigation controls. As such, they are more likely to offer incentives for energy-saving pumps. Sub-metering water systems are excellent tools to benchmark water use by system and to measure outcomes of conservation efforts.

IMAGE FROM TOP: PRIVA AND GRODAN; SILVER BULLET.

SECTION 11

Operational Considerations

Far too often a facility is designed or retrofitted without proper planning and resources for upkeep. Unlike cultivation facilities of a few decades ago, indoor farms and modern, weather-respondent greenhouses are more machines than buildings, always running from the day production begins. Water is used by nearly every component of this machine. Facilities that do not create a culture of sound operations and preventative maintenance do so at the peril of their business. Develop preventative maintenance schedules, SOPs, and accountability, while developing tracking for equipment usage, repairs, and inventory.

On-site Testing Equipment - Every CEA facility should budget for routine water testing using a reputable water testing laboratory. Your water treatment supplier, fertilizer supplier, or installer may be able to recommend a suitable lab.

Supplementing lab analyses, every operation should have water testing equipment on hand. A best practice is to have calibration standards, spare parts, small testing supplies, and SOPs readily available for on-site testing, along with records for accountability. Training should be documented to ensure each employee conducts the tests in an identical manner. Some of the testing equipment is familiar to most cultivators: hand-held or countertop pH and EC meters,

SECTION 11 CONTENTS:

> On-site Testing Equipment

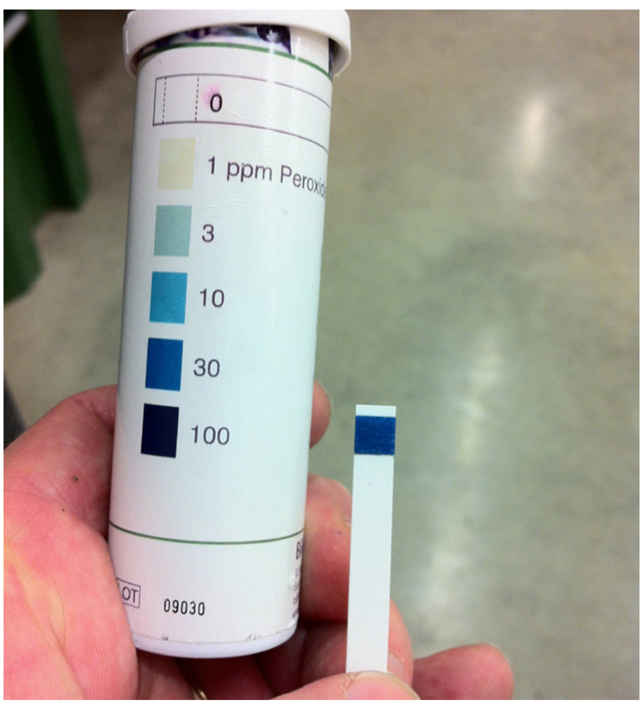
> Planning for Maintenance and Supplies

> Staffing for Water Treatment Operations

alkalinity meters, nitrate meters, or–for hydroponic systems–dissolved oxygen meters.

Growers using ozone, chlorine, or chlorine dioxide disinfection should have a hand-held **oxidation-reduction potential (ORP) meter** used for monitoring. Recently, growers have been trained by the University of Florida to test for **colony forming units (CFUs)** of aerobic bacteria in water using 3M Petrifilm. Measures of >10,000 CFU/ml of bacteria pose a high risk for biofilm development in plumbing and reservoirs.[109] These disposable tests are sold in packs of 25 and cost just a few dollars each. As will be discussed later in the Guide, control of biofilm is one of the highest priorities due to its ability to harbor plant and human pathogens. There are also test kits or colorimetric test strips for on-site analysis of ozone, peroxyacetic acid and chlorine dioxide disinfectants. Find more information for on-site and laboratory testing for biological water quality recommended by the University of Florida in the Resources section.[110]

Figure 43. Colorimetric test strip for hydrogen peroxide concentration.



Planning for Maintenance and Supplies - Water treatment experts agree that the long-term business success of a CEA facility hinges on having a culture of accountability for the upkeep of mechanical operations. This does not require that operations dedicate long periods of time to upkeep, but rather commit to consistent, frequent checks for normal operations and calibration. All employees in cultivation operations should know when something does not look, sound, or smell right, and know the key personnel accountable for each piece of equipment.

SOPs for scheduled maintenance should be developed using manufacturer recommendations, with user manuals of all equipment on-hand and available in clearly designated areas. The standard control sequences documentation for equipment should include system schematic flow diagrams in addition to the written sequences of operation. A best practice is to keep hard copies of this information in a common area in case a power outage or weather emergency reduces access to online versions. Using software designed to track maintenance, repairs, and inventory with automated electronic reminders is greatly encouraged.

While not intended to be a comprehensive manual, water treatment experts agree on what is most often overlooked for water treatment systems and irrigation maintenance:

- Routine sensor calibration;
- Routine water quality sampling;
- Evaluation of screens, filters, pumps, and gaskets;
- Sediment tank maintenance;
- Inspection of storage tanks for cracks and corrosion;
- Lubrication of bearings and pumps;
- Scheduled rebuilds of pumps and ozone systems;
- Blowdowns of boilers and chillers;
- Checks for the integrity of UV lamps;
- Backflow regulator testing;
- Cleaning of grime off equipment;
- Water system pressure checks;
- Irrigation leak checks;
- Checks for capacity and flow rates of drip systems;
- Checks for evaporative cooling pad leaks and bleed-off rates;
- Replacement of injector diaphragms and seals;
- Checks for clogged fogging and misting nozzles;
- Routine maintenance for high-pressure fogging pumps.

109 Fisher, P., Meador, D., Parke, J., Wick, R., & Argo, W. (2011). Water Quality: What's In Your Water? : Biological water quality. Greenhouse Management. October 2011.

110 cleanwater3.org (n.d.). Where can I get my irrigation water checked for Pythium or Phytophthora spores? Retrieved May 7, 2023, from https://www.cleanwater3.org/launch.asp?id=6&fsID=2

Spare parts and consumable goods for water treatment that should always be kept on hand include the following:

- Filters and filter media;
- Membrane filters;
- Sensor probes;
- Pumps;
- UV lamps;
- Cleaning and anti-scaling products.

Staffing for Water Treatment Operations - For large facilities with a significant amount of remediation equipment and storage capacity, a full-time employee may be needed to ensure the proper operation of water treatment. This person should have certified professional water treatment experience–look for titles along the lines of "Water Operations Engineer." One source of training is the Water Environment Foundation. General maintenance technicians with plumbing and electrical training can serve under the W.O. Engineer while also sharing duties in other areas. It is common for facilities, both small and large, to contract maintenance of their systems through service agreements with third parties.

SECTION 12

Policy Considerations

The industry and academic experts on the Water Circularity Working Group (WCWG) identified potential issues that can be resolved with help from the public sector. They also identified practices and technologies suitable for incentive programs by governments and utilities, as well as research for priority funding. Though the U.S. Department of the Interior regulates natural resources such as the Colorado River Basin through federal law, individual states have authority to regulate water reuse.

The following summary is not intended to be prescriptive, as the WCWG agreed that more research and in-depth conversation needs to take place in order to make specific recommendations to regulatory agencies. Resource Innovation Institute, to fulfill one objective of its USDA-NRCS funding grant, titled 'Data-Driven Market Transformation for Efficient Controlled Environment Agriculture,' convened a Policy Working Group to undertake this goal, and their work has been published independently of this Best Practices Guide: Controlled Environment Agriculture (CEA) Policy Guide: Benchmarking, Rate Design, Water Efficiency, and Additional Policies.

SECTION 12 CONTENTS:

> Current Status of Water Reuse Regulation

> Addressing the Energy-Water Nexus

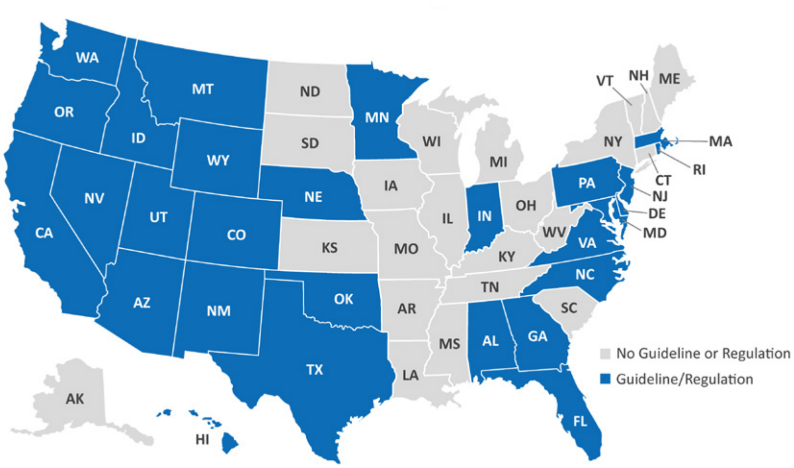
> Suggested Research Priorities

> Suggested Equipment and Methods Incentives

> Suggested Useful Metrics

Current Status of Water Reuse Regulation - The Environmental Protection Agency EPA does not require or restrict any type of water reuse.[111] Generally, states maintain primary regulatory authority (i.e., primacy) in allocating and developing water resources. Some states ha." established programs to specifically address reuse, and some have incorporated water reuse into their existing programs. The EPA, states, tribes, and local governments implement programs under the *Safe Drinking Water Act* and the *Clean Water Act* to protect the quality of drinking water source waters, community drinking water, and water bodies like rivers and lakes. Together, these two acts provide a foundation from which states can enable, regulate, and oversee water reuse as they deem appropriate. The EPA provides many resources, including the online search tool for regulations, Regulations and End-Use Specifications Explorer (REUSExplorer).

Figure 44. States with water reuse regulations.



According to Texas A&M University, many states now require a water discharge permit to control irrigation runoff, including from greenhouses. These permits regulate the runoff volume that flows into surface and groundwater reserves and in many situations, "...the quantitative discharge standards are vague and each case is based on the best professional judgment of the regulatory agency."[112] Common features of these regulations include retention of all irrigation runoff and the first two inches of stormwater runoff. Irrigation runoff typically must have a pH between 6-9, nitrate and ammonia levels of less than 2 ppm, acceptable levels of solids, and contain no pesticides.

But what of indoor farms and grow pods, often located in or near urban centers? Local regulators may not have codes for agriculture facilities located in their jurisdiction, and the WCWG experts report that these facilities are typically the subject of regulations for industrial operations. This compounds the already variable regulatory requirements that exist across state and local jurisdictions, where there can be differences even by crop type. Therefore, a best practice for designing and retrofitting CEA facilities is to establish sound communication with local utilities early in the planning process.

Addressing the Energy-Water Nexus - Remediating and recycling water requires energy for treatment equipment, pumps, controllers, and more. As a rule of thumb, the more impaired a water source, the more energy will be required for its remediation. The volume of water stored can impact energy usage as well. Rainwater stored outdoors may require heating to avoid freezing and may need to be heated or cooled prior to irrigation. Additionally, stored water requires circulation to avoid creating an environment for biological growth, and that circulation system consumes energy.

As was noted earlier, higher water quality is required for recirculation systems than for single-pass irrigation, as well as for longer-term crops over short-term crops. Achieving this high quality comes at an energy cost. Any recommendations for water circularity in CEA facilities and for water policy must address this energy-water nexus. Equipment selection, water conservation practices, green infrastructure, and renewable energy sources are among the tools to address energy consumption.

Fertilizer is energy intensive to manufacturer and transport, accounting for nearly one-third of the energy cost of crop production.[113] Unlike field farming, a typical CEA facility applies water-soluble fertilizer formulations via the irrigation solution. One study from the United Arab Emirates reported indoor horticultural substrate culture and hydroponics resulted in fertilizer savings of at least 55% compared with conventional outdoor farming.[114] By reducing leaks and irrigation overapplication, the CEA industry can reduce fertilizer costs and the energy required for its manufacture.

IMAGE: U.S. EPA

111 U.S. EPA. (2023). Basic Information about Water Reuse | US EPA. (March 8, 2023).
112 US EPA. (2023)
113 Amenumey, S. E., & Capel, P. D. (2014). Fertilizer Consumption and Energy Input for 16 Crops in the United States. Natural Resources Research, 23(3), 299–309.
114 AlShrouf, A. (2017). Hydroponics, Aeroponic and Aquaponic as Compared with Conventional Farming. © 2012-2021 American Academic Scientific Research Journal for Engineering, Technology, and Sciences.

Importantly, due to the water-energy nexus, water circularity could be incentivized to conserve both electricity and water.

Suggested Research Priorities - The WCWG suggests public and private funding should be allocated for research on fertigation water rebalancing and recirculation, ion-specific sensor technology, discharge water quality specifications, and bioremediation systems, both outdoor and containerized for indoor use. Smart controls, artificial intelligence modeling of plant growth, and beneficial microbes are also suggested. Modifications of HVAC and HVAC-D equipment to reduce metal, oil and chemical contamination of condensate would greatly benefit the CEA industry, as well as crop breeding programs for drought tolerance and disease resistance in CEA environments.

Suggested Equipment and Methods Incentives - Utility incentives for adopting LED grow lighting over high-intensity discharge (HID) lamps have proven very successful in ensuring more resource-efficient CEA facilities are being built or retrofitted. Similar incentives would improve water circularity and—due to the energy-water nexus described above—help reduce energy. Among technologies the WCWG suggests be considered for incentives are water flow sensors and sub-metering equipment so that measurement can take place, following the adage of "you can't manage what you don't measure."

Recapture and remediation equipment, including tanks, disinfection and purification systems, and monitoring probes are among the green infrastructure suggested. Bioremediation systems and practices, both outdoor and containerized for possible indoor use, should be incentivized. Condensate recapture and recycling is another practice that many strongly advocate being incentivized, as it is easier to remediate than most other water streams.

Suggested Useful Metrics - The WCWG suggests areas for further discussion on metrics for water circularity, specifically a change from a focus on "flow rate" to a "water quality" mindset. The discharge water might be assessed and compared to the incoming source water quality, as a "before and after" scenario. The discharge might be assessed for total dissolved solids, for example.

Another useful metric would define the ratio of water coming into the facility to that being discharged. It may be useful to measure water according to productivity, rather than usage per unit of area. However, such a productivity unit would vary greatly according to crop, so may not be a fair comparison between facilities growing different species or product types. Water productivity metrics would also vary according to location, as water is cheaper and less regulated in some regions, with less incentive for producers to conserve. Leach fraction for horticultural substrate culture may also be considered, though this also would vary across facilities, crops, and cultivation systems.

Lastly, the CEA sector is attempting to contrast its value from traditional field agriculture as it earns more shelf space in grocery stores. Given the difficulty measuring CEA facilities against one another as described above, it may make sense to focus on the larger, more relevant picture. For example, Duijvestijn Tomatoes in the Netherlands reports each kilogram of its greenhouse tomatoes requires less than 4 gallons (15 liters), compared with 16 gallons (60 liters) for plants from field production.[115] Metrics that would provide a valid comparison of water use and environmental impact between field-grown produce versus CEA produce may prove enlightening to the public and would certainly be beneficial for the industry.

Figure 45. Purple pipes indicating recycled water at the Controlled Environment Agriculture Center, University of Arizona.

[115] Viviano, F. (2017, September). The Netherlands: This tiny country feeds the world. nationalgeographic.com. Retrieved May 10, 2023, from https://www.nationalgeographic.com/magazine/article/holland-agriculture-sustainable-farming

Links to Further Resources

Review of Zero Liquid Discharge Cultivation in The Netherlands

cleanwater3.org website

Grower data tools, trackers, and calculators from cleanwater3.org

Mobile grower apps from e-Gro

Back Pocket Gower: tools and calculators

Best Practice Guidelines for Greenhouse Water Management

Control of Waterborne Microbes in Irrigation: A Review

Designing a Water Treatment System, Introduction and Importance

Water Treatment Guide for Greenhouse & Nurseries

Constructed Wetlands: A How To Guide for Nurseries

Water Treatment for Pathogens and Algae

Reverse Osmosis Optimization

Michigan Compost Operator Training Guidebook

Water Flow Model Tool

Evaporative Cooling Pads - Maintenance for a Longer Life

The Water Footprint Assessment Manual

Online Tool for Estimating Return-on-Investment for Water Recycling at Nurseries

Safe Drinking Water Act

Clean Water Act

Guide to Minimize Microbial Food Safety Hazards for Fresh Fruits and Vegetables

Labs for Identification of Pathogens in Water

Microbially Healthy Water in Greenhouse Horticulture

Nutrient Solutions for Greenhouse Crops

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