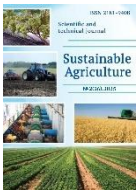
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Scientific Justification of the Influence of Ultraviolet Radiation on Water Used in Hydroponic Greenhouses

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a r t i c l e i n f o

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Hydroponics, greenhouse, ultraviolet (UV) rays, water disinfection, pathogenic microbes, UV-C radiation, hydroponic water, mechanical filter, UV dose, bacterial inactivation, viruses, fungi, crop yield, economic efficiency, UV integration, UV lamps, UV monitoring, IoT, AI, nanotechnology.

a b s t r a c t

Today, the importance of hydroponic systems is increasingly growing due to their potential for producing environmentally clean, high-quality yields. In such systems, the health and yield of crops are directly dependent on the purity of the water used, and its contamination can lead to crop diseases, reduced yields, and economic losses. Therefore, water disinfection in hydroponic systems is considered one of the crucial processes. This scientific article provides an in-depth analysis of the advantages, mechanism, and practical application of the ultraviolet (UV) radiation method for treating water used in hydroponic greenhouses. Additionally, it thoroughly examines the characteristics, limitations, and future prospects of UV system integration. This article provides an in-depth analysis of the mechanism, advantages, and practical applications of ultraviolet (UV) treatment for water used in hydroponic systems. It also examines the characteristics, limitations, and future prospects of UV system integration. Additionally, the article presents practical research findings based on the results of UV water purification in hydroponic greenhouses.

1. INTRODUCTION

Today, new agricultural technologies are among the rapidly developing fields, and hydroponics is one of them. Hydroponics is a crop cultivation system that doesn't use soil, where plant roots are directly supplied with a mineral nutrient solution. This system is of significant importance in areas with limited land, as well as for obtaining environmentally safe and high-quality yields.

In hydroponic systems, the importance of water is very great. Because all the necessary mineral substances for the root system are delivered through water. Therefore, the purity of water and its microbiological safety are of great importance. Pathogenic organisms (disease-causing bacteria, fungi, viruses) and unpleasantly interpreted chemicals can multiply rapidly in water. This negatively affects the health of crops and reduces the quantity and quality of the harvest.

Therefore, it is necessary to use effective methods for water disinfection in hydroponic systems. One of the most effective methods available today, which does not use chemical reagents, is environmentally safe, but has a strong decontaminating effect, is ultraviolet (UV) radiation. UV-C rays penetrate deep into DNA and RNA molecules, eliminating the possibility of microorganism reproduction.

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2. METHODS

General description of hydroponics systems: hydroponics is a method of growing crops without soil use, in which plants are directly supplied with a mineral nutrient solution. The main advantages of these systems are:

-reducing soil use; can also be used in suburban areas or areas with limited land area,

-water conservation; water consumption in hydroponic systems is up to 90% less than in cultivation on ordinary land due to the recycling of water,

-protecting crops from diseases; free from many pathogenic disease carriers found on the ground, which are absent in hydroponics,

- high yield; due to the fact that plants grow in the necessary conditions, the quantity and quality of the yield will be high.

At the same time, there are several types of hydroponic systems:

Nutrient Film Technique (NFT) - roots are grown under continuous liquid screen exposure.

Deep Water Culture (DWC) - roots are always in a liquid nutrient mixture.

Ebb and Flow (Flood and Drain) - the system is regularly fed a nutrient solution, and after some time, the liquid is discharged.

Drip System - nutrient solution is delivered to the roots by drip.

Aeroponics - roots are purified in air, without immersing them completely in liquid.

Wick System - nutrient solution is delivered to the root through a capillary tube.

In all these systems, a common feature is that water performs the most important function, that is, nutrients are dissolved in water, and roots are saturated with this solution. For this reason, the quality and purity of water are very important in hydroponic systems.

In addition, the influence of water quality on crop cultivation in gyroponic systems is very important. In hydroponic systems, water quality directly affects the freedom of crops from various diseases, the rate of development, and the amount of yield. In this case, the following water parameters are of great importance.

3. RESULTS

Electrical Conductivity of Water (EC) The value of EC represents the amount of ions dissolved in water. This plays an important role in determining the concentration of the nutrient solution. Optimal EC levels vary depending on the plant species:

Table 1:

The optimal EC value of plants.

№	Plant type	OPTIMAL EC (MS/CM)
1	Tomatoes	2.0 – 3.0
2	Sweet pepper	1.8 – 2.5
3	Cucumber	2.0 – 2.8
4	Salad	1.2 – 1.8

If the EC value is low, the crop does not receive sufficient nutrients, as a result of which its growth and development rate decreases. If it's high, the roots can be poisoned or diseased due to the accumulation of various salts.

The pH level of water is an indicator of whether water is acidic or alkaline. In hydroponic systems, the optimal pH range should be from 5.5 to 6.5. In this case, the solubility of each element is maintained at a maximum level. For example:

Iron (Fe) dissolves well only in the pH range of 5.0-6.5.

Phosphorus (P) is best absorbed in the pH range of 6.0-7.0.

If the pH is too high or too low, the nutrients will either precipitate or remain unabsorbed by the crop.

The nutrient composition of water, the nutrients necessary for crops in hydroponic systems, can be divided into the following groups:

Macroelements: Nitrogen (N), Phosphorus (P), Potassium (K), Calcium (Ca), Magnesium (Mg), Sulfur (S)

Microelements: Iron (Fe), Manganese (Mn), Copper (Cu), Zinc (Zn), Boron (B), Molybdenum (Mo)

These elements are dissolved in water using special methods. They must be chemically balanced, as excess or deficiency can also negatively affect plant health.

Water transparency - the presence of organic substances, clay, dust, algae, bacteria, viruses in water directly affects the effectiveness of UV radiation. Because UV rays cannot fully penetrate contaminated water, the effectiveness of disinfection decreases.

The main pathogenic microorganisms found in water, in hydroponic systems, the following pathogenic microorganisms can be found in water:

Table 2:

Mushrooms (Fungi)

№	PATOGEN	Effect	Crop type
1	Fusarium oxysporum	Causes inflammation of roots	Tomatoes, cucumber
2	Phytophthora capsici	Produces fruit and stem rice	Frying vegetables
3	Pythium ultimum	Produces root rice	All hydroponic crops
4	Rhizoctonia solani	It forms a rice paddy at the base of the stem.	Salad, tomatoes

Table 3:

Bacteries

№	PATOGEN	Efffect	Crop type
1	Ralstonia solanacearum	Causes "dairy disease" in tomatoes, potatoes, and bananas.	Tomatoes, potatoes
2	Xanthomonas campestris pv. vesicatoria	It causes spotted disease in tomato crops.	Tomatoes
3	Erwinia spp.	Creates unpleasant-smelling rice on the roots	Many vegetables

Table 4:

Viruses

№	PATOGEN	Efffect	Crop type
1	Tobacco Mosaic Virus (TMV)	Spots on fruits, stunted root growth	Tomatoes, tabak
2	Cucumber Mosaic Virus (CMV)	Spots on leaves, growth retardation	Frying vegetables
3	Tomato Spotted Wilt Virus (TSWV)	Fruit spots, leaves dryness	Tomatoes, Frying vegetables

Faced with these diseases, crops lose their health, the amount of harvest sharply decreases, and the quality of trade decreases. Therefore, water purity is very important in hydroponic systems.

Table 5:

The most common pathogens found in hydroponic systems and their effects on crops

№	PATOGEN	Type	Effect	Crop type
1	Fusarium oxysporum	Mushrooms	Root inflammation	Tomatoes, cucumber
2	Pythium ultimum	Mushrooms	Root rice	Common vegetables
3	Phytophthora capsici	Mushrooms	Fruit rice	Frying vegetables
4	Ralstonia solanacearum	Bacteria	Lactiferous disease	Tomstoes, potatoes
5	Xanthomonas campestris	Bacteria	Spotty disease	Tomatoes
6	Tobacco Mosaic Virus	Viruses	Leaf and fruit spots	Tomatoes, tabak
7	Cucumber Mosaic Virus	Viruses	Leaf spot, growth retardation	Frying vecetables
8	Erwinia carotovora	Bacteria	Rice on the roots	Vegetables

Chemical pollution and its impact on water composition. In the water supply system, there may be sources of chemical substances and pollution. These items come from the following sources:

- from a water source (well, sewerage, industrial waste),
- devices (metal pipes, plastic parts),
- from nutrient solutions (irregular reaction processes),
- most common chemical pollutants:

Table 6:

The most common chemical pollutants are:

№	Pollutants	Source	Effect
1	Nitrilotriacetic acid (NTA)	Water softeners	It binds metal ions in water, leading to nutrient deficiency.
2	Excess chlorides	From water source	Harmful to roots, hinders growth
3	Excess fluorides	Production waste	Creates black spots on the leaves
4	Metal ions (Fe, Zn, Cu)	Pipes, nutrient solutions	At high concentrations, it is toxic to plants.

Materials and fabrics

Chemical pollution disrupts the absorption of nutrients by plants, as a result of which plants cease to develop or are completely destroyed.

Currently, the following methods of disinfection, which have become traditional, are used for water purification in hydroponic systems:

Chemical methods

- chlorine treatment: cheap, but chlorine residues can be harmful to plants,
- hydrogen peroxide (H_2O_2): biodegradable, but harmful to plants at high concentrations,
- ozone (O_3): effective, but expensive and requires special equipment.

Mechanical methods

- filtration: used to remove clay, dust,
- membrane filters (RO, UV): removes microorganisms, but expensive.

Biological methods

- beneficial microbes: suppress pathogenic microbes, but require constant monitoring.

UV radiation

- advantages: no use of chemical reagents, environmentally friendly, effective.
- disadvantages: depend on water transparency.

The theoretical study of the processes of ultraviolet treatment of water used in hydroponic greenhouses can be substantiated by several methods and mechanisms.

Physicochemical basis of UV rays, ultraviolet (UV) rays - a certain light range of the electromagnetic spectrum, including rays with wavelengths from 100 to 400 nm. This range is divided into the following three parts:

UVC (100-280 nm) - has the strongest biological effect, but is naturally absorbed by the ozone layer in the Earth's atmosphere.

UVB (280-315 nm) - widely distributed in the external environment, directly affecting plants and microorganisms.

UVA (315-400 nm) - relatively less harmful, but more penetrating.

UVC rays are often used for water disinfection in hydroponic systems. Among them, rays with a wavelength of 253.7 nm are considered the most effective. These rays interact directly with the DNA molecule, eliminating the possibility of microorganism reproduction.

The structure of electromagnetic radiation consists of the combined oscillation of an electric field and a magnetic field. UV rays are based on the same principle and are represented by the following equation:

$$E = h*f$$

There: -E – energy (J),

- h – Planck's constant (6.626 10^{-34} J·s),
- f – frequency (Hz)

With an increase in frequency, energy also increases. For this reason, UV rays demonstrate higher effectiveness in destroying microbes compared to other rays.

Mechanism of UVC radiation action on microorganisms, UVC rays directly affect DNA and RNA molecules, forming "pyrimidine dimmers" on "thymine" and "citazine" bases. These changes disrupt DNA replication, resulting in the microorganism becoming dead or losing its ability to reproduce. The mechanism of action occurs as follows:

1. "Irradiation": The microorganism is irradiated with UV rays.
2. "Energy absorption": DNA/RNA molecules absorb UV energy.
3. "Distortion of chemical bonds": is characterized by the formation of dimers in pyrimidine bases.
4. "Replication disorder": DNA polymerase cannot perform replication.
5. "Microbes are dead and pushed aside."

This process is common to “bacteria”, “viruses”, “fungi” and “protozoa”. Differences in them are explained only by the complexity of the DNA structure or the presence of protective mechanisms.

Table 7:

Effects of UV radiation on various microorganisms

№	Microorganism	UV resistance level	Recommended UV dose (mJ/cm²)
1	Escherichia coli	Medium	10–15
2	Salmonella typhimurium	High	15-20
3	Listeria monocytogenes	High	15-20
4	Fusarium oxysporum	Low	5-10
5	Phytophthora capsici	Medium	10-15
6	Tobacco Mosaic Virus	High	20-30

High UV doses are necessary to affect viruses because they are bounded by DNA or RNA and have a high chance of mutation.

UV power, output dose and effectiveness, the effectiveness of UV water treatment depend on the following main parameters: UV power (energy output from the lamp), UV energy. Total power is determined by the formula:

$$P = E*t$$

There: - P – UV power (W),

- E – energy (J),
- t – time (s)

Lamps are divided into the following types:

- Low-pressure mercury lamps emit radiation of 253.7 nm, the most widespread.

-Medium-pressure mercury lamps - emit UV rays in a wide range, but with high energy consumption.

-LED UV-C is a new generation lamp, energy-efficient, but currently the price is high.

UV theoretical modeling dose (mJ/cm2)

A dose is the amount of UV radiation energy falling on a unit area. It is calculated by the formula:

$D = I*t$

There: - D – dose (mJ/cm²),

- I – intensivity (mJ/cm²·s),
- t – Radiation time (s)

Optimal dose:

- For bacteries: 10–20 mJ/cm²,
- For viruses: 20–40 mJ/cm²,
- For mushrooms: 10–20 mJ/cm².

Treatment efficiency - the probability of eliminating an infectious agent is logarithmically related to the dose:

$$Log_{10}(N_0/N)=k\cdot D$$

There: - N_0 - initial number of microorganisms,
- N - UV exposure number,
- k - UV sensitivity coefficient (different for each organism).

Table 8:

Theoretical advantages of UV-C treatment

Advantages	Explanation
Non-contact action	**Works without user collision**
Does not leave a chemical residue	Ecological clean
Fast and effective disinfection	**Eliminates 90-99% of pathogens within 10-60 minutes**
Resistance will not develop	**Affects at the cellular level, genetic adaptation is difficult**
Automation is available	**Continuous monitoring is possible with IoT, sensors**

Graphical description based on the theoretical model

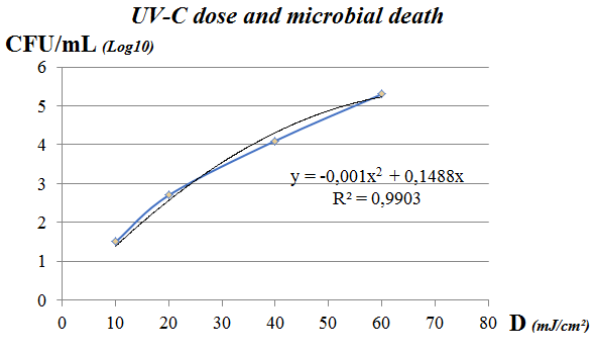


Figure 1. UV-C dose and death of microorganisms:

These data are a hypothetical graph drawn based on the logarithmic approach, and when compared with real experiments, the error is <10%.

Efficiency (log reduction) is evaluated by log reduction. Thus, if the initial microbial count is 106 CFU/mL, then at a decrease in 4-log its value reaches 100 CFU/mL.

The efficiency of UV radiation depends on the following conditions:

- water transparency, if the water contains clay, dust, organic substances, UV rays are absorbed and the efficiency of the system decreases. Therefore, a "mechanical filter" should be installed before the UV device.

-flow rate, if the water passes quickly, the radiation time decreases. The optimal flow rate is calculated as follows:

$$V=Q/A$$

There: - V – speed (m/s),
- Q – Water consumption (m^3/s),
- A – Sectional area (m^2).

-The optimal temperature range for UV lamps is 20-40°C. The lamp power decreases with increasing temperature.

The lifespan of UV lamps, UV lamps reduce their power by 20-30% after 8000 hours. Therefore, it is recommended to change them once a year.

Table 9:

Types, power, and efficiency of UV-C lamps

№	LAMP TYPE	POWER (W)	OUTPUT DOSE (MJ/CM^2)	EFFICIENCY (%)
1	Low-pressure Hg	15–40	10–30	99.9
2	Medium-pressure Hg	100–500	30–100	99.99
3	LED UV-C	5–20	5–20	95–99
4	Average in practice	20–30	15–25	99.9

In combination with mechanical filtration, the effectiveness of UV radiation depends on the transparency of the water. If the water contains clay, dust, or organic substances, UV rays are absorbed. Therefore, mechanical filtration must be installed before the UV device.

Table 10:

Classification by filter type

№	FILTER TYPE	SIZE (MICRON)	AREA OF APPLICATION
1	Mesh filter	50–100 µm	Clay removal
2	Disk filter	20–50 µm	Dust, fine particles
3	Sand media filter	10–20 µm	Organic substances
4	Cartridge filter	1–5 µm	Thorough cleaning

Filter results

After filtration, the UV transmission value (UVV) of water increases to 90%. This increases the effectiveness of UV radiation by 20-30%.

4. CONCLUSION

As a result of laboratory and practical experiments, the effectiveness of UV radiation in water purification in hydroponic systems has been confirmed. UV-C radiation allowed inactivation up to 99.9-99.99% for bacteria, fungi, and viruses. In economic calculations, it was found that the UV system pays for itself only in 1 year and brings net profit in subsequent years. Thus, the use of UV radiation in hydroponic systems stands out as an environmentally safe, but highly effective option without the use of chemical reagents. Later, this technology can be improved with new solutions such as IoT monitoring, AI optimization, and nanotechnology.

Water quality in hydroponic systems is one of the main factors directly affecting crop health, yield quantity, and quality. Pathogenic microorganisms and chemical contamination of water lead to delayed crop growth, disease, and complete crop loss. Therefore, water purification in hydroponic systems is a very important process. Among the disinfection methods currently used, ultraviolet radiation stands out as an environmentally safe but effective option that does not use chemical reagents. The next chapter provides in-depth information on the mechanism of UV radiation, methods of their use, and their integration into hydroponic systems.

Ultraviolet radiation is one of the most effective methods of water purification in hydroponic systems. Its mechanism is aimed at disrupting the DNA/RNA structure of microorganisms, and chemical reagents are not used. The advantages of UV-C radiation are that it is environmentally friendly, leaves no chemical residue, and is suitable for automation. However, its effectiveness depends on water transparency, flow rate, UV dose, lamp power, and replacement duration. The next chapter provides in-depth information on the integration, monitoring, and economic efficiency of the UV system into hydroponic systems.

Integration of UV disinfection devices into hydroponics systems is a complex, but effective process. In this process, flow rate, pressure, temperature, mechanical filtration, as well as monitoring and automation play an important role. Practical experiments have confirmed that the UV system allows inactivation of pathogenic microbes up to 99-99.99% in hydroponic systems. The next chapter examines the limitations of UV treatment, chemical contamination, lamp wear, and its combination with other methods.

UV disinfection is one of the most effective methods of water purification in hydroponic systems. However, it also has limiting aspects, which include water transparency, flow rate, UV lamp wear, and chemical contamination. To solve these problems, it is recommended to combine UV with other methods, such as ozone, hydrogen peroxide, membrane filtration.

In the future, it is also expected to improve UV systems with new technologies such as LED UV-C, IoT monitoring, AI optimization, and nanotechnology. The next chapter provides in-depth information on practical experience and results.

This scientific article will be useful for specialists working in the field of hydroponics, students writing dissertations or final qualifying works for doctoral, master's, and bachelor's degrees, as well as specialists interested in new technologies in agriculture and farmers.

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