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Treatment of Greywater Washing Machine Through Cold Plasma for Hydroponic Cultivation

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ABSTRACT

Greywater, which forms 50-80% of domestic wastewater, is increasingly viewed to reuse in agriculture due to its low content of pathogens and the global need to conserve fresh flows of water resources. This research investigates the efficiency and sustainability related to the use of Atmospheric Cold Plasma (ACP) for greywater treatment meant for hydroponic cultivation of lettuce. ACP-treated greywater had improved quality, attaining a reduced Chemical Oxygen Demand by 75%, with better nutrient content, such as 23.5 and 8 percent increase in total N and K, and a slight adjustment in pH values to those optimal for lettuce cultivation. Due to this, some healthier and more vigorous lettuce plants developed, characterized by an average of 5 more leaves in each sample, darker and greener foliage, and higher chlorophyll content. The results obtained from this study prove that ACP is a much better and more efficient method for greywater treatment as compared to the traditional methods of physical, chemical, and biological treatment. Hence, it opens up new avenues toward establishing certain techniques in providing sustainable agriculture use and water resource management. Further research should be done on applying ACP technology in greywater treatment for expanded farm application.

1. Introduction

Nowadays, one of the most important problems that the world encountered is the shortage of water resources. This issue causes considerable effects including crop yield reduction, and limited agricultural activities immediately and then it will affect impaired sustainability, irrigation demands increment, and compromised food security during a long-term process (Liu et al., 2022). Major issues such as population growth and economic development lead to an increase in water demand. According to (World Health Organization, 2017) and (Boano et al., 2020), accessibility to clean water is impossible for about one-third of the global population. Since water demand is increasing, and crop irrigation is among the largest parts of it, concerns about these problems increased, too.

To solve this problem, scientists and researchers investigated solutions for reusing water. Through these solutions, water can be reused after filtration and sanitation by multiple methods. Therefore, freshwater consumption will be saved and the total amount of water consumption will decrease, which can protect people and ecosystems from possible difficulties. In this order, greywater has been introduced. The recyclable part of wastewater is called greywater, which includes 50% to 80% of wastewater (Ludwig, 2012). Due to their low level of pathogens, recycling of greywater became popular among specialists (Li et al., 2023). Greywater includes the waste from the bath, shower, hand basin, clothes washing, laundry tray, and dishwasher water, as well as some kitchen sink water. Some available research does not include kitchen wastewater (Li et al., 2009). Besides that, crop irrigation is a significant water consumer; 70% of all withdrawals of freshwater globally are used for agriculture, roughly (Yin et al., 2022). Therefore, the reuse of greywater for crop irrigation, as one of the biggest participants in clean water consumption, is suggested and as a result, worries about the global water crisis will be reduced. As greywater contains dangerous contaminants, including pathogens and heavy metals, high efficiency of filtration and decontamination is required (Finley et al., 2009). Also, concerns about the illness risk of greywater irrigated crops are negligible as no significant difference between bacterial levels on plant surfaces in plots irrigated with greywater and tap water was observed (Jackson et al., 2006).

Many different ways of greywater treatment were recommended which can be classified into physical, chemical, and biological methods or a combination of them (Joz Ghasemi et al., 2016). In physical methods, physical forces purify greywater. They were the first method to treat greywater. They have low costs, and it is being tried to use

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the most power for this treatment. This method includes garbage collection, particle collection, sedimentation, floating, and filtration (Rastogi, 2019). Microorganisms have a prominent role in biological methods because they absorb organic materials for cell production and energy (Mandal et al., 2011). The treatment method based on the separation or transformation of pollutant substances by chemicals and their chemical reactions is called the chemical method (Joz Ghasemi et al., 2016). The selection of greywater treatment methods is influenced by their ability to manage fluctuations in the concentration of organic, inorganic, and pathogenic substances in the incoming greywater. They must also consistently generate an output that is of suitable and safe quality to meet the necessary water quality standards for reuse (Rao et al., 2020).

Those methods showed their potential and worked well. They have, however, problems, difficulties, and disadvantages. Physical treatment of greywater is challenging because quality fluctuates significantly over a short time period, which makes it difficult to respond to the coincidence with the shock loading of organic matter and chemicals (Khan et al., 2022). Besides, the traditional chemical treatment methods would not fully comply with environmental quality criteria since they might not remove all quality effluent water-linked parameters (El Qrenawi et al., 2022). The major drawback of biological treatment is the time taken in the process of therapy: it demands a large area for treatment and storage of water, and therefore, it leads to high capital and operating costs (Dhiman & Sharma, 2022). Biological treatment also leads to the development of unwanted microorganisms producing gases and foul odors, which may limit its applicability in some instances (Chen et al., 2020). In addition, though adequate for eliminating organic pollutants, it may fail to take care of all sorts of contaminants, such as detergents and cosmetic wastes; hence, additional treatment steps are required for complete purification (Hussain et al., 2022). It follows that developing a simple and cheap treatment system with minimal human labor and no additives requirement has not been amply researched.

Atmospheric Cold Plasma (ACP) treatment illustrated decontamination and sterilization by electrical discharge. Plasma is formed by introducing high energy to gas samples, leading to ionization and the production of smaller ionic species. Within plasma systems, more than 75 ionized and neutral species, along with UV-visible light, contribute to over 500 chemical reactions. These reactive species interact with the components of treated materials, with the generated ozone and reactive ions inducing modifications in molecular structures and their interactions with biomolecules in the matrix (Mahanta et al., 2022).

ACP offers notable advantages in greywater treatment over traditional methods, including effective degradation of resistant contaminants like pharmaceuticals and dyes, significant pathogen inactivation within short durations, and eco-friendly operation at ambient temperatures, enhancing system efficiency (Maybin et al., 2024; Tang et al., 2024; Hamza et al., 2023; Saedi et al., 2024). Meanwhile, generating Ozone during this treatment plays an essential role in decontamination (Rao et al., 2020). However, challenges remain in scaling ACP for large-scale applications due to economic constraints, and its efficacy can vary depending on the water matrix (Hamza et al., 2023; Saedi et al., 2024). In this research, the ACP system was developed to investigate its effect on greywater sterilization and treated water performance on crop irrigation of lettuce. Greywater extracted from a washing machine has been collected and after the ACP treatment, it was used as an irrigation source for lettuces. In order to understand the effectiveness of the treatment system, the lettuces on the control side were irrigated using non-treated greywater. Since the study aimed to propose a procedure for less water consumption, due to less water and resource usage (Pomoni et al., 2023), a hydroponic system was developed for lettuce cultivation. According to the changes in the quality parameters of the greywater alongside quality, color, and growth parameters of the lettuces, a conclusion was made regarding the usefulness of this treatment method.

2. Experimental

2.1. Plant Preparation

Seedlings of *Lactuca sativa* L. Parris island lettuce were provided from a commercial greenhouse located in Nazarabad (Karaj, Iran). The seedlings were grown for 1 week in the greenhouse and then, moved to the Biosystems Engineering Laboratory of IROST (Ahmadabad Mostoufi, Tehran, Iran) for the test.

2.2. Greywater Sampling

Greywater was collected from a washing machine (Kenwood model superspin 1000) in a private apartment located in Tehran, Iran. Urban water in Tehran with 50ml of liquid detergent(liquid laundry detergent brand Tage, for all types of clothes, softener-included) was used to wash woolen clothes at 40°C.

Greywater includes some microbes, nutrients, and organic matter which will lead to odor nuisance (Siegrist, 1977). Furthermore, storing greywater for longer than 24 hours in warm weather for safe use will cause the occurrence of pathogens (*Pseudomonas aeruginosa, Aeromonas spp.*) and biofilm growth (*Legionella spp., Mycobacterium avium*) in still water.

Considering the above conditions, Ten liters of the evacuated greywater were collected from the effluent as shown in Fig. 1. Then it was poured into plastic bottles and transferred to the biosystems engineering laboratory at IROST (Ahmadabad Mostoufi, Tehran, Iran) to put in a refrigerator in less than a day from the collection time.

2.3. Pretreatment

Greywater contains particles that are between 10 to 100µm (Spychała et al., 2019) so they have to be removed before the

Fig. 1. The greywater sampling method.

treatment stage. Thus, the greywater was poured into a 1.5 liter reservoir, 30 centimeters above the surface and moved to the water purification pump (Soft Water TYP-2500 model) on the surface by gravitational force. Then, it passed through a 10µ membrane filter by the pump. Afterward, the 250ml of pretreated greywater was collected in a 400ml beaker.

2.4. Main Treatment

The experimental setup included an aquarium air pump, a 400mm beaker, a glass tube, an air stone (sphere-shaped, made of ceramic, 3cm diameter), an aluminum net, and a wire. The aluminum net was affixed to the outer surface of the glass tube and grounded to serve as a dielectric barrier. Plasma generation was facilitated by a high-voltage power source capable of delivering up to 30W and 12kV voltage. The pulse generator operated at a frequency of approximately 6.7kHz throughout the experimentation. A non-insulated wire with a diameter of 1.2mm was connected to the high-voltage power source and positioned within the glass tube parallel to the aluminum net, creating a strong electric field. When a high-voltage pulse was applied, it ionized the gas molecules in the air between the electrodes, creating a plasma discharge. This process involved the generation of reactive species, ions, and electrons under ambient conditions, forming the cold plasma used in the treatment (Mahanta et al., 2022). To minimize the formation of air bubbles, an air stone was introduced into one end of the glass tube via an aquarium tube to inject the plasma into the greywater. The air stone also ensures the even distribution of plasma-treated air and enhances the treatment's efficiency by maximizing contact between the reactive species and water components (Neto et al., 2008). The opposite end of the tube was connected to the aquarium air pump using a plastic tube. To prevent foaming of the water upon air injection, the entire apparatus was placed within a 2000ml beaker (Fig. 2).The treatment method used in this work was similar to the previously described Dielectric Barrier Discharge (DBD) method (Traylor et al., 2011). The DBD system is simple and compact; it consists of an aquarium pump, a high-voltage power supply, and a 10µ filter. Furthermore, the DBD system was demonstrated to treat fast, with the capability of treating greywater to a suitable state for crop irrigation within one time; hence, it provides a quick and appropriate remedy. The antimicrobial plasma properties utilized in our experimental setup have been reported in the literature by (Sharma et al., 2018).

Treatment by plasma was applied to 250ml of grey water for 1hr. To avoid the action of ozone on the health of the plant, the plasma-treated water was rested for 20min before applying it so that the ozone residuals in the water could dissipate (Von Gunten, 2003).

2.5. Cultivation Method

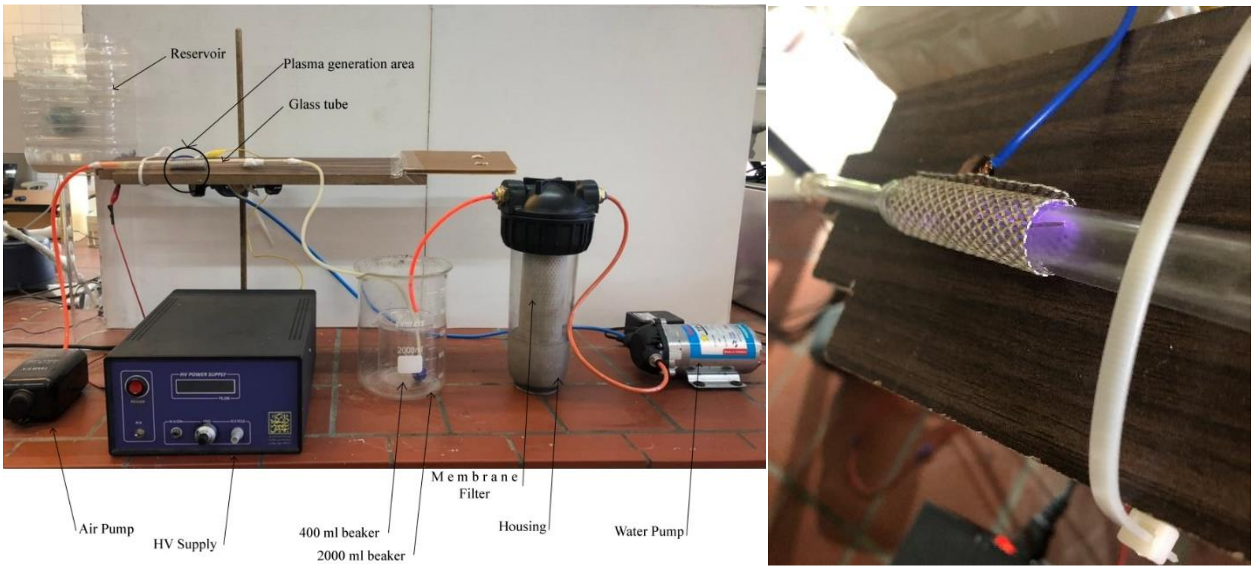
The seedlings were placed in four hydroponic pots replicated for treated greywater or control. Mechanical support for the stabilization of seedlings was done using pumice stones following (Sharma et al., 2018), who recommended the use of inert media. The light was provided by an LED lamp (21W, 50Hz, 220-240V, 65002K).

Each plant received 300 ml of treated greywater. To maintain the optimal air temperature for lettuce growth, which ranges from 24 to 28˚C (Carotti et al., 2021), a commercial thermometer was used to monitor the ambient temperature in the growth area. Since the plants use a certain amount of water, additional greywater was treated in advance to ensure a consistent supply for the plants in subsequent weeks. Each week, 15ml of treated greywater was used for irrigation per treatment, while each control plant received 15ml of untreated greywater.

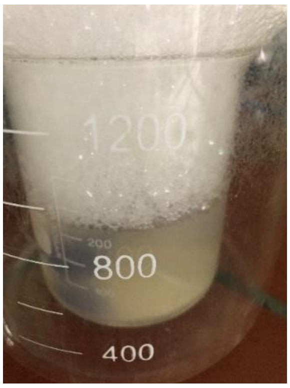
3. Method

3.1. Parameters Measurement

The different parameters of greywater were measured before they were used for crop irrigation. The greywater was tested before and after the treatment to represent the effect of ACP. The initial pH value was measured using a pH meter (FGiran pH meter). Electro-conductivity (EC) was determined with an EC logger (AZ Instrument Taiwan, model 8306AZ). Chemical Oxygen Demand (COD) was measured based on the closed reflux method using vials (Hach Company). Due to the faster results and reproducibility of the COD test, which correlates with Biochemical Oxygen Demand (BOD), COD is sometimes used to estimate BOD levels. COD testing evaluates all chemically oxidizable substances (Ghaly et al., 2021). Moreover, the inability of BOD to indicate the oxidation state of an organic substance makes the COD test more popular (Raposo et al., 2008). Total nitrogen (N) and total phosphorus (P) were analyzed using in-house methods, while total potassium (K) was tested according to the ISIRI 11114-3 standard in the laboratory.



a)



b)

Fig. 2. Pretreatment and treatment system. a) The whole system and b) Greywater treatment

3.2. Plant Quality Assessment

The quality of plants irrigated with treated greywater was assessed using the Dickson Quality Index (QID), a widely recognized metric for evaluating plant robustness and biomass distribution. The QID was calculated using Eq. (1):

$$\mathrm{QID} = \frac{\text{Total dry weight}}{\left(\frac{Stem's\,length}{stem's\ diameter} + \frac{shoot\ dry\ weight}{root\ dry\ weight}\right)} \qquad (1)$$

The QID metric provides a composite measure of plant quality, considering factors such as biomass allocation and structural stability. A higher QID indicates better plant vigor and suitability for agricultural applications (Eskandari et al., 2019; Dickson et al., 1960).

The wet weight of stems and roots was measured using a digital scale (RADWAG, model WLC 2/A2). After calculating the damp weight, crops were placed in an oven (F.A.G Industrial Group) at 75°C for 24h. Later on, the dry weight of the roots and stem was measured using a digital scale. Root and stem lengths were measured with a 30cm ruler having 1mm precision. Leaves longer than 1cm were included in the leaf count parameter.

Furthermore, Leaves' colors were measured using a spectrometer (TES, model 135A), which recorded the leaf color parameters in the CIELAB color space (Setyawan et al., 2018).

3.3. Statistical Analysis

For analysis of these results, a T-test would be most ideal since this can be quite effective in the comparison between paired data-samples (Costello & Watts, 2020).

Table 1. Initial values of the greywater parameters.

Greywater Type \ Parameter	pH	EC(µs/cm)	Total P(ppm)	Total K(ppm)	Total N(%)	COD(mg/L)
Control	6.50	1086	0.7	29.7	0.17	2120
Treatment	6.26	1231	0.6	32.2	0.21	540

The results enable the researcher to establish whether any given observed difference exists outside a normal range and to provide indications with respect to ACP efficiency for increasing greywater qualities and influencing plants' growth in such cases. Analysis was done using SPSS software, version 21. Before conducting the T-test, all data were tested for normality using the Shapiro-Wilk test to ensure that the assumptions of the parametric analysis were met. If data were not normally distributed, appropriate transformations were applied, or alternatively, non-parametric tests were considered. In this case, $p < 0.05$ was considered as the significance level. All the experiments were performed in quadruplicates. A comparative analysis was done to study the impact of ACP treatment on critical parameters such as pH, EC, COD, nitrogen, phosphorus, and potassium levels, and plant quality parameters.

4. Results and Discussion

4.1. Greywater Quality

The greywater parameters have been measured and represented in Table 1. Important greywater indexes have been displayed to evaluate the effect of ACP on the growth of lettuces and to assess its potential as a hygienic treatment method. ACP might influence lettuce growth by altering each of the parameters.

In the case of evaluating the effect of ACP on the growth of the lettuces, it is necessary to know how it influences the greywater and then, discover its potential as a hygienic treatment method.

ACP treatment altered several greywater parameters that could potentially affect lettuce growth. Among these, pH showed a slight decrease after treatment, although the change was not statistically significant. This adjustment brought the pH closer to the optimal range of 5.5–6.5 for hydroponic lettuce cultivation (Susanti & Purwanto, 2023). Such a shift likely enhanced nutrient availability by increasing the solubility of phosphorus and other essential minerals, thereby improving nutrient absorption (Mohamed & Abdalla, 2013).

Similar reductions in pH have also been observed in other treatment methods. For example, Fountoulakis et al., (2016) reported a pH decrease using a mulch retention filter, while Estrada et al. (2020) observed a comparable effect with a Submerged Membrane Bioreactor (SMBR). These studies suggest that pH reduction is a common outcome of greywater treatment, regardless of the specific method employed, and could contribute to enhanced nutrient uptake and plant growth. The slight decrease in pH after ACP treatment, despite being subtle, appears beneficial for lettuce cultivation. This observation, supported by comparisons with conventional methods, highlights ACP's potential as an effective and hygienic treatment approach for greywater.

Electro-Conductivity (EC) is a critical parameter for assessing ion concentration in greywater, directly influencing nutrient availability and uptake by plants. Low EC levels can severely limit plant growth and nutrition by reducing root nutrient uptake capacity (Sharvelle et al., 2010; Domingues et al., 2012). In this study, ACP-treated greywater exhibited EC values closer to the optimum range for lettuce cultivation, approximately 1300µS/cm (Miller et al., 2020), which likely contributed to improved plant quality.

The effect of ACP on EC is attributed to the generation of reactive species through ionization and electrical breakdown during treatment. This increase in ion availability ensures a more balanced nutrient supply, facilitating better growth conditions. Similar findings have been observed in other treatment methods, such as biofiltration and constructed wetlands, which also improved EC values to support plant growth (Fountoulakis et al., 2016; Estrada et al., 2020). Subsequently, the ACP-induced adjustment of EC levels appears to play a pivotal role in enhancing lettuce growth. By bringing greywater closer to the optimal EC range, ACP demonstrates its potential not only as a hygienic treatment method but also as a tool for improving the nutritional environment for hydroponic cultivation.

The levels of total nitrogen (N) and total potassium (K) significantly increased after ACP treatment, leading to a 27% and 8% rise in total N and K, respectively. This increase is likely due to the dissolution of reactive nitrogen and potassium species generated during the ACP process (Xie et al., 2020). In contrast, total phosphorus (P) levels decreased, potentially due to advanced oxidation processes that broke down phosphorus compounds into less detectable forms (Gururani et al., 2021).

Compared to traditional treatment methods, ACP offers unique advantages by preserving and even enhancing the nutrient content of greywater, reducing the need for additional fertilizers. As reported by Fountoulakis et al., (2016), significant nutrient removal in greywater treated with a Submerged Membrane Bioreactor was observed, including 40% nitrogen and 69% phosphorus reduction. In another study, Jesse et al., (2019) observed slight increases in total nitrogen (5.45%) and total phosphorus (1.4%) when greywater treated with sand filtration was supplemented with Post-Hydrothermal Liquefaction Wastewater (PHW). It can be concluded that ACP's ability to increase nitrogen and potassium content while reducing phosphorus levels presents a dual benefit of enhancing greywater quality for agricultural reuse. This nutrient enrichment eliminates the need for external fertilizer supplementation, making ACP a sustainable and resource-efficient greywater treatment option.

The ACP treatment led to a roughly 75% decrease in Chemical Oxygen Demand (COD), enhancing the suitability of greywater for lettuce irrigation and promoting healthy plant growth. This decrease in COD is largely attributed to the breakdown of organic pollutants through advanced oxidation processes, a characteristic feature of ACP treatment (Nguyen et al., 2019). The efficiency of ACP in reducing COD surpasses that of many conventional treatment methods, highlighting its superiority as a treatment technology.

For comparison, several studies have reported lower COD reductions using other treatment methods. March et al., (2004) applied a nylon sock-type filter followed by sedimentation and disinfection to bath greywater, achieving a 54% reduction in COD. Similarly, Sostar-Turk et al., (2005) used membrane ultrafiltration with a 0.05 µm pore size for laundry greywater pretreatment, which resulted in a 56% decrease in COD. Finley et al., (2009) employed a system consisting of coarse filtration and slow sand filtration with a hydraulic retention time (HRT) of about 24 hours, yielding a 20% reduction in COD. Lin et al., (2005) combined disinfection with electro-coagulation, achieving a 60% reduction in COD, while Pidou et al., (2008) integrated coagulation with magnetic ion exchange resin, which led to a 63% reduction in COD for shower greywater. Biological treatment methods have also been studied, with the UASB reactor at ambient temperature treating mixed greywater and achieving a maximum COD reduction of 41% (Elmitwalli et al., 2007). Hernandez et al., 2008 reported a 50% COD reduction using a UASB reactor with an HRT of 7 to 12.5 hours.

In conclusion, ACP is more effective than many traditional methods in reducing COD, offering a highly efficient and sustainable solution for treating greywater in agricultural applications.

4.2. Lettuces Growth

The results of the growth parameters have been mentioned in Fig. 3.

The EC level of treated greywater (1231µS/cm) was close to the recommended range for hydroponic lettuce production (1300µS/cm) (Mohamed & Abdalla, 2013), contributing to better plant growth compared to untreated greywater. The reduction in pH after ACP treatment brought it closer to the optimal range, enhancing nutrient absorption by plants. Additionally, the increased total nitrogen (N) in treated greywater resulted in higher stem and root wet weights. In contrast, untreated greywater, with surfactant contamination, hindered plant growth (Eriksson et al., 2002), an issue mitigated by ACP's antibacterial ozone properties (Pichara Morais et al., 2024).

The results of the QID measurement can be observed in Fig. 4. It has been demonstrated that nutrient uptake was higher in the treatment lettuces. An increase in total N, total P, total K, and nitrate concentration helped the lettuce to have higher nutrient uptake. The effect of the cleaner environment of treated greywater is also inevitable in this improvement.

4.3. Color

The leaf color parameters are shown in Fig. 5. In the Lab color space, L represents lightness (0 for black and 100 for white), a indicates the gradient from green to magenta (-128 for green to 128 for magenta), and b represents the gradient from blue to yellow (-128 for blue to 128 for yellow) (Abbadi et al., 2020).

Lower A and L values indicate greener and darker leaves, respectively, suggesting fresher plants. This is important for consumer satisfaction, as the color of fruits and vegetables significantly influences consumer perception (Calín-Sánchez et al., 2020). The greener leaves likely result from higher chlorophyll content, which correlates with increased total nitrogen levels, as confirmed by Punith et al., 2019.

Cold plasma treatment has been shown to improve the chemical composition of irrigation water, enhancing nutrient availability, which in turn benefits lettuce growth (Gamal et al., 2024). Additionally, ACP preserves natural pigments like chlorophyll, which are crucial for the green color of lettuce, and may even enhance other pigments (Ramezan et al., 2023). Although studies indicate that cold plasma treatment can cause minor color changes, it generally maintains or improves the visual quality of vegetables (Ramezan et al., 2023). The results observed in this study align with these findings, as ACP-treated lettuce exhibited enhanced green coloration, likely due to improved chlorophyll content and nutrient availability.

5. Conclusions

In conclusion, the study showed that the treatment of greywater with ACP was an effective and sustainable method for improvement in quality, rendering it fit for lettuce hydroponic cultivation. Treatment with ACP significantly improved key parameters of greywater. The treatment led to a significant decrease in COD-analyzable and essential nutritive elements, for example, total nitrogen (N) and total potassium (K), and a slight modification of pH to more optimal ones. In detail, there was a 75% COD reduction by ACP that was significantly higher than those reported for some other physical, chemical, and somewhat biological treatment approaches, which ranged between the second and 60%, respectively, thus testifying ACP superior efficiency at organic pollutants decomposition. The increase in EC of the greywater brought it closer to optimal lettuce-growing conditions, making nutrients get into the plant well. Even though the total P reduction was a bit low, further management by the advanced oxidation processes in ACP indicates how this

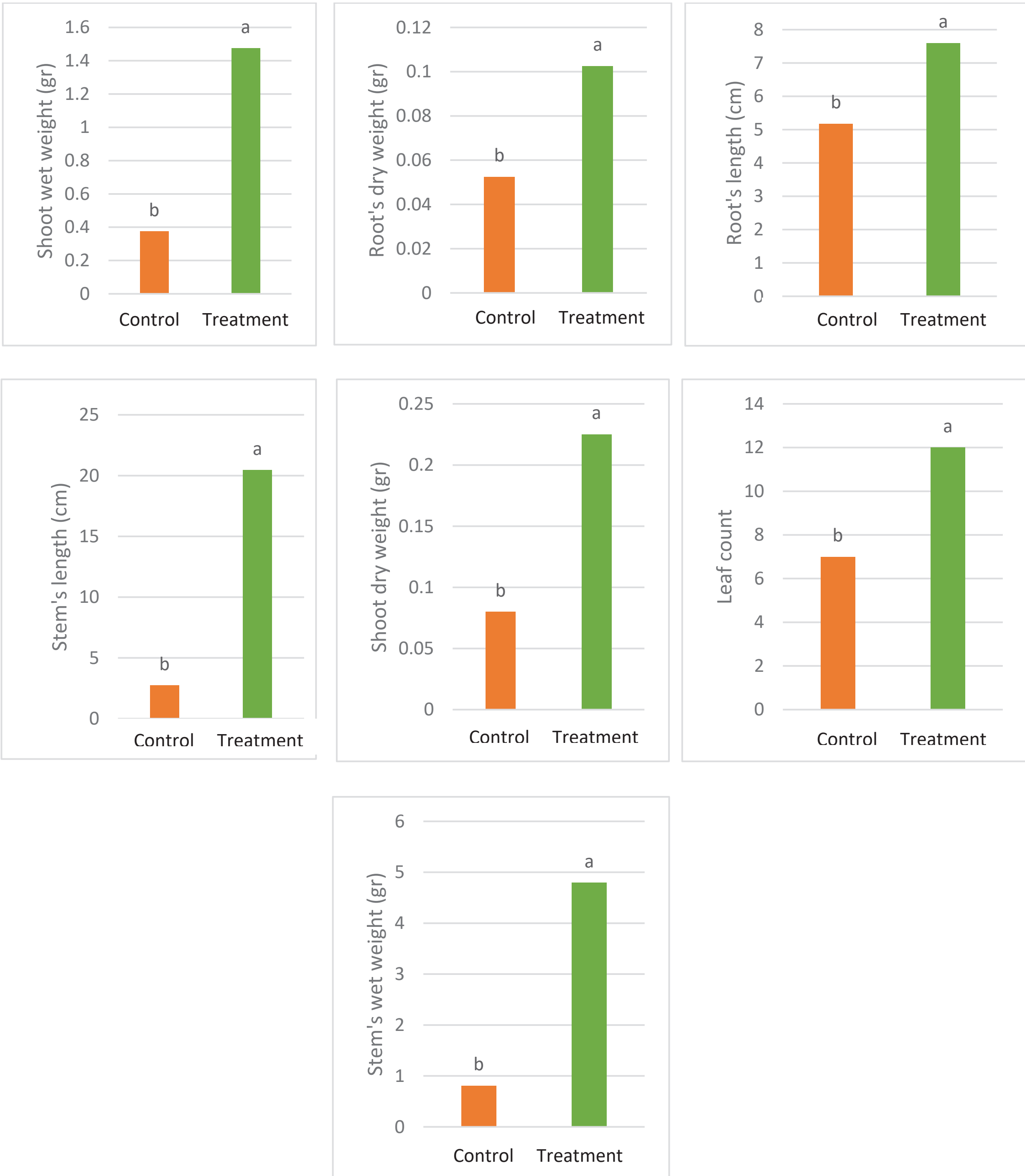


Fig. 3. Plant growth parameters

method is suitable for nutrient profile balance without having to resort to other fertilizers. The plant growth parameters thus significantly improved lettuce growth when the lettuce plants were irrigated with ACP-treated greywater. The conclusion could be derived from the fact that more leaves were there, the plant foliage was greener and darker, and the chlorophyll content was found to be on the higher side, which indicates better and more vigorous plant growth. Also, a means through which high prospects of customer satisfaction were indicated is the improved look and quality of the lettuces, as visual appearance plays a significant role in consumer inclination. In general, the ACP treatment provides a potential solution to water scarcity because it enables the reuse of greywater in agriculture. This method does not only meet the challenge of effective decontamination of greywater but also supports sustainable agriculture as freshwater becomes rare and chemical fertilizer use diminishes. The results of this study suggest more research and maybe an extension to the application of ACP technology in the treatment of greywater for sustainable crop production.

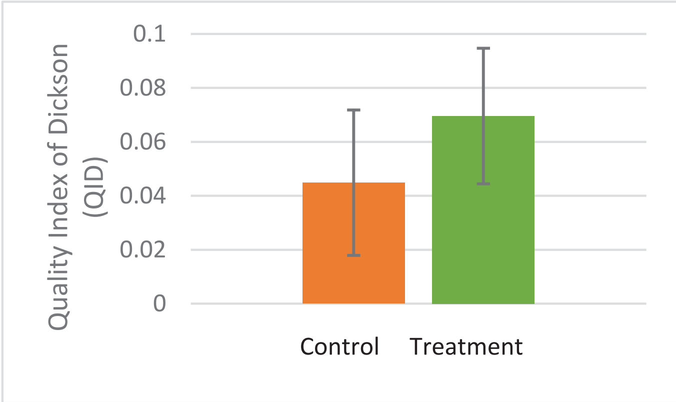


Fig. 4. QID values

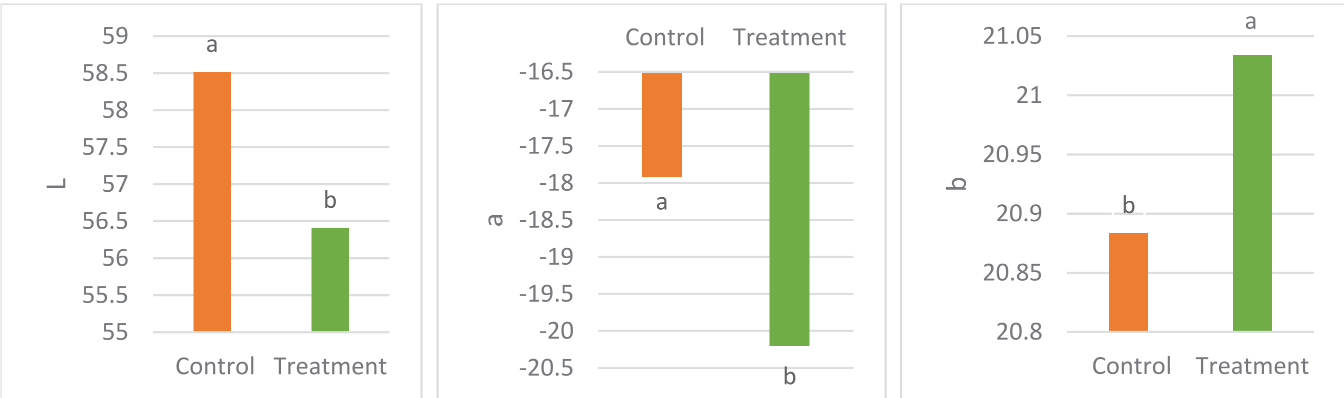


Fig. 5. Color parameters of the lettuce

6. Nomenclature

ACP	Atmospheric Cold Plasma
COD	Chemical Oxygen Demand
EC	Electrical Conductivity (µS/cm^2)
QID	Quality Index of Dickson

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