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Engineering Hydroponic Systems for Sustainable Wastewater Treatment and Plant Growth

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Abstract: This study aimed to optimize hydroponic systems for simultaneous wastewater treatment/nutrient recovery and plant growth. Various hydroponic systems (geyser pump, full flow, ebb and flow, nutrient film techniques, aeroponics, misting) were constructed using 160 mm PVC waste pipes supported on a 200 L reservoir. Secondary wastewater was used to cultivate rice (*Oryza sativa*), ivy (*Hedera helix*), tomatoes (*Solanum lycopersicum*), and wheatgrass (*Triticum aestivum*). Parameters such as plant height, biomass, retention time, temperature, conductivity, pH, dissolved oxygen, ammonia, nitrite, nitrate, total phosphorus, COD, BOD, TDS, TSS, and TS were monitored. Results indicated minor variations in pH, EC, and TDS over time in systems with and without plants, with no significant differences. Turbidity decreased significantly ($p \leq 0.001$) in all systems, while TOC levels reduced significantly ($p \leq 0.05$) only in the presence of plants. BOD and COD levels exhibited similar reductions with and without plants. Ammonium levels decreased in plant systems, while nitrite levels remained unchanged. Nitrate levels increased significantly in plant systems, and phosphate levels showed no significant difference. Additionally, significant ($p \leq 0.001$) plant length (12.84–46.75%) and biomass (31.90–57.86%) increases were observed in all hydroponic systems, accompanied by higher levels of dissolved oxygen (36.26–53.65%), compared to the control (4.59%). The hydroponic system that created a moist atmosphere, either through misting or aeroponics, thus allowing maximum access to oxygen, showed the greatest growth. This study confirmed the importance of oxygen availability to the rhizosphere for plant growth and wastewater treatment. It also identified limitations and investigated the impact of dissolved oxygen concentration on plant–microorganism interactions. Optimal oxygen availability was achieved when plant roots were exposed to a moist atmosphere created by the hydroponic system through aeroponics or misting. The findings have practical implications for hydroponic system design in urban vertical farms, benefiting wastewater treatment, mitigating eutrophication, and reducing food miles.

Keywords: hydroponics; design; municipal wastewater; rhizosphere; oxygen; urban farm

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1. Introduction

The urbanization trend has caused a spatial shift in human habitation, impacting the capacity of cities to match the historical ecological support once provided by rural areas through ecological services (ESs) [1] (which are products of nature, directly enjoyed, consumed, or used to yield human well-being [2]. Urban areas face ongoing challenges such as water scarcity, nutrient-depleted soils, food miles, and pollution, which are expected to intensify with population growth and climate change [3].

To address these challenges and meet the growing needs of urban populations, innovative approaches are essential, as cities heavily depend on ESs for vital benefits such as water and air purification [4]. Sewage mining offers an ecologically and cost-effective decentralized approach for effluent treatment, mitigation of eutrophication, and local cultivation of valuable crops. Wetlands, known as "nature's kidneys," serve as ESs for solar-driven, decentralized phytoremediation and nutrient extraction from waste streams [5]. However, constructed wetlands face limitations in urban settings, such as the requirement for large horizontal space, mainly relying on anaerobic processes [6], and being limited in plant choices to those with roots adapted to low-oxygen environments [7].

To overcome these limitations, a vertical wetland engineered on the facades of buildings, which increases oxygen to the root zone, is proposed. To do this, we need to ecologically engineer the wetland ES in a systematic approach. Hydroponics, a soilless method of agriculture, have traditionally been used to maximize crop yields by optimizing plant root access to nutrients and oxygen [8]. As a significant part of wastewater treatment in constructed wetlands occurs in the root zone [5], a hydroponic system offers a potential answer to wastewater that can be effectively treated to meet legislative standards using different hydroponic systems (Figure S1 in Supplementary Materials) [9–11]. Additionally, this approach enables the cultivation of food crops and oxygen-demanding plants, establishing an urban vertical farm. It promotes at-source treatment, reduces food transportation distances, facilitates nutrient recycling, and fosters circularity.

Gebeyehu [12] reported a 48% nitrogen removal efficiency with a gravel and ebb–flow system from brewery wastewater. Rababah et al. [13] demonstrated the effectiveness of the nutrient film technique (NFT) system for domestic sewage treatment through biofilm establishment [14]. However, Vaillant et al. [15] found that the hydroponic system failed to meet the required phosphorus (P) and nitrogen (N) removal levels due to insufficient dissolved oxygen (DO). High biochemical oxygen demand (BOD) hindered the nitrification process by creating oxygen competition between nitrifying bacteria and other microorganisms. Significant nitrification occurred only when BOD was below 45 mg L^{-1} [15]. Limited research exists on the application of aeroponics for wastewater treatment and the effects of different hydroponic methods on DO levels, plant growth, and microorganisms [9,10,15]. Oxygen and nutrient access in the rhizosphere are the key property for maximizing plant growth and wastewater treatment efficiency in these systems [16–19]. Therefore, this research aimed to investigate the limiting criteria for such a hydroponic system, specifically access to oxygen. The experiment discussed in this paper aims to investigate how different methods of hydroponics influenced the accessibility of oxygen to the rhizosphere. To achieve this, the specific objectives of the experiment were to (1) confirm that oxygen is the key property for the growth of the plants and treatment of secondary wastewater, and (2) analyze how different hydroponic systems treat and affect growth in plants.

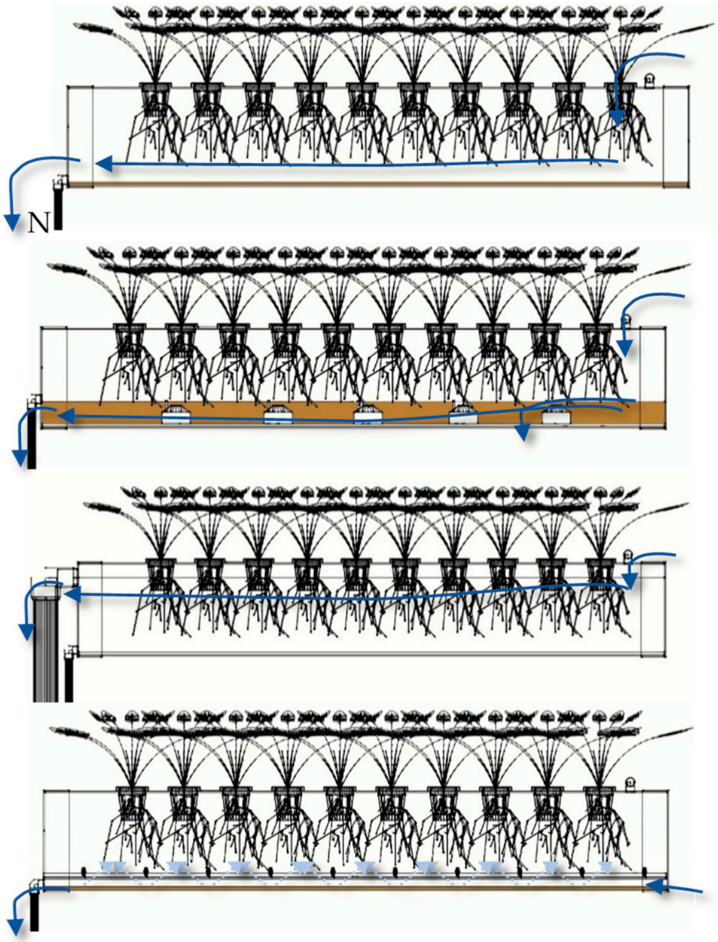
2. Materials and Methods

2.1. Preparation of the Plants for All Experiments

Rice (*Oryza sativa*, macrophyte and one of the most grown food crops), wheatgrass (*Triticum aestivum*, also a popular food crop) ivy (*Hedera helix*, a known phytoremediator), and tomatoes (*Solanum lycopersicum*, nitrophilic and commonly grown food crop) were propagated (rice and wheatgrass) or cloned (tomatoes and wheatgrass) from an original mother plant according to the method outlined by Alexander [20]. This was started 4–6 weeks prior to each experiment, and a specific hybrid line was exclusively employed to maintain genetic uniformity and control diversity. After substantial growth, 60 plants of similar root length within the range of ±2 cm were selected from the propagators. The mass and length of the individual plants were measured and recorded before and at the end of each experiment.

2.2. Hydroponic Systems

Six hybrids were used in the following systems: geyser pump (GP), full flow (FF), ebb and flow (EF), NFT, aeroponics (AP), and misting (MT) (the fogponic unit), along with a control (C) that was just a reservoir (Figure S2). Each system was constructed using PVC waste pipes with a diameter of 0.16 m and a length of 1 m, capable of accommodating 10 plants per pipe, and a reservoir tank with a volume of 200 L (Figure S3). The secondary wastewater used in the experiment was obtained from Bellozanne Wastewater Treatment Works in Jersey, and the reservoirs were directly filled from nearby secondary clarifiers. The wastewater was recirculated for a week, with flow rates varying based on the hydroponic method. The systems were arranged in pairs, utilizing the reservoir as support. A pump at the bottom of the reservoir circulated the wastewater through the system and back into the reservoir. Figure 1 illustrates the different system arrangements.



GP and NFT systems, indicating the flow of the system.

MT system, indicating the flow of the system. The return pipe is positioned to maintain a depth of the misters to allow them to function properly, at all times creating a mist.

EF and FF systems have a top return pipe for full flow, with an additional smaller bottom return pipe in EF for the Ebb and Flow effect during pump cycles.

In the AP system, indicating the spray of this system. The sewage enters a pipe, sealed at the end, under pressure. The flow exits the spray nozzle as a spray.

Figure 1. Cross-section drawing of the different hydroponic setups and flow direction of sewage.

All drawings were made using the software Sketchup (version 2021) and Microsoft Office 365, all being licensed under University College London.

2.3. Parameters for the Experiments

Table 1 outlines the variables that were analyzed and/or controlled in this study.

The experiment consisted of 5 runs with tomatoes, rice, ivy, wheat, and no plants. Each run was conducted twice over 4 weeks. Analysis was performed at intervals of 0 h, 24 h, 48 h, 72 h, 120 h, and 168 h. Samples of 1 L were taken at 0 h and 168 h for COD and BOD analyses in the first two experiments. Sewage was replaced at the end of 168 h and again at the start of the second run. After filtration through a 45 µm membrane filter, samples were stored in 50 mL sterile bottles and refrigerated until analysis. On-site analysis included pH (Hanna HI 9813-5, Smithfield, RI, USA), TDS, TSS, TS, and DO (Extech DO_2 Meter 407510, Nashua, NH, USA). COD (HACH DR2000 Photometer, Loveland, CO, USA) and BOD analyses were performed at the States Jersey Laboratory, while Ion and IC (Dionex ICS 1100, Sunnyvale, CA, USA) and TOC (Shimadzu TOC-L, Kyoto, Japan) samples were transported to the UK for analysis at UCL within 4.5 h.

Table 1. The variables within the study.

Variable	Frequency	Methods	Reference
Length	Start and End	Simple scale measuring method	[21]
Biomass	Start and End	Dry-weight measuring method	[21]
Retention Time	168 h	Set by the time of the experiment	
Volume	200 L	Spectrophotometric method	[22]
Temperature	1 min intervals	Partial immersion method	[23]
Electrical Conductivity	24 h intervals	Spectrophotometric screening method	[23]
pH	24 h intervals	Electro method	[23]
Carbon Dioxide	1 min intervals		ISO 12039:2001
DO	24 h intervals	Azide modification Winkler's method	[23]
Free Ammonia	24 h intervals	Molecular absorption spectrophotometry	[23]
Nitrite	24 h intervals	Molecular absorption spectrophotometry	[23]
Nitrate	24 h intervals	Molecular absorption spectrophotometry	[23]
Total Phosphorous	24 h intervals	Molecular absorption spectrophotometry	[23]
COD	24 h intervals	Closed reflux titrimetric method	ISO 6060
BOD	24 h intervals	5-Day dilution BOD test method	ISO 5815
TOC	24 h intervals		ISO 8245:1999
Humidity	1 min intervals		ISO 4677-1:1985
TDS	24 h intervals	Thermal evaporation method	[23]
TSS	24 h intervals	Filtration and thermal evaporation method	[23]
TS	24 h intervals	TDS = TS − TSS	[23]

Note: chemical oxygen demand (COD); total organic carbon (TOC); total dissolved solids (TDS); total suspended solids (TSS); total solids (TS).

2.4. Statistical Analysis

All data were first evaluated for homogeneity of variance and normality using Bartlett's and Levene's tests. Statistical significance between parameters and plants in each experiment was examined using the paired *t*-test and Spearman regression in SPSS 22. Significance was determined at a *p*-value of $\leq$0.05. [24].

3. Results

Experiments on rice, ivy, tomatoes, and wheat lasted 7 days each run, and a total of 2 runs were undertaken. However, the second run with tomatoes was excluded due to their unexpected death within 24 h, and as a result, only the data from the first run were utilized for the tomato runs. This was possibly caused by high sodium chloride levels or nearby vegetation spraying (Figures S4 and S5). The cause remains unclear, despite no significant recorded environmental conditions.

3.1. The Plants

All plants created dense roots, particular the AP and GP systems, with GP roots vacating the effluent pipe (Figure S6). The dense mat of roots serves as an anchor for plants and facilitates biofilm growth. However, it posed challenges for accurate plant measurements when removing them due to tangled roots, requiring cutting for removal (Figure S7). The difference between the mass plants before and at the end of each experiment is shown in Figure 2. Overall, ivy showed the highest plant mass, ranging from 34.60 to 86.20 g, followed by wheat (3.20–43.00 g) and rice (6.60–23.90 g). It can be seen from Figure 2 that there was a significant mass increase for all plants ($p \leq 0.001$).

The length of the plants at the start and end of the experiment is shown in Figure 3. EF (10–25 cm) and FF (10–5 cm) systems showed the lowest growth, while MT (28–60 cm) and AP (25–50 cm) presented the highest growth.

The hydroponic system that provided the highest average plant growth (Figure 4) was MT (90.15%), followed by AP 86.95%), NFT (59.83%), GP (50.81%), EF (39.33%) and FF (15.59%). In terms of average plant mass, again MT (136. 30%) showed the highest performance, followed by NFT (101.09%), AP (91.33%), EF (74.07%), GP (69.98%) and FF (27.78%).

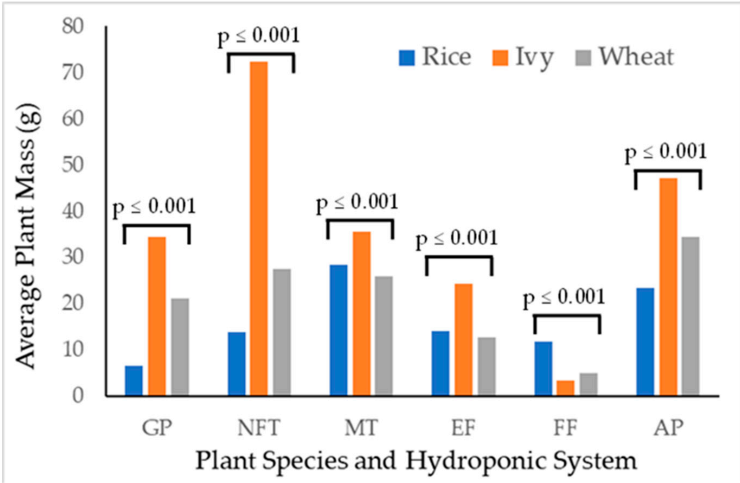


Figure 2. Change in mass (g) for all experiments for the rice, ivy and wheat grass. The tomato experiment is not shown as the plant growth failed. Geyser pump (GP), nutrient film technique (NFT), misting (MT), ebb and flow (EF), full flow (FF), aeroponics (AP).

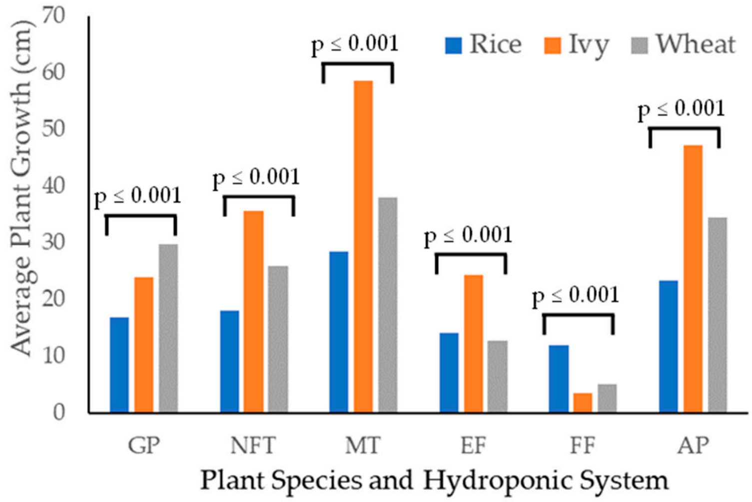
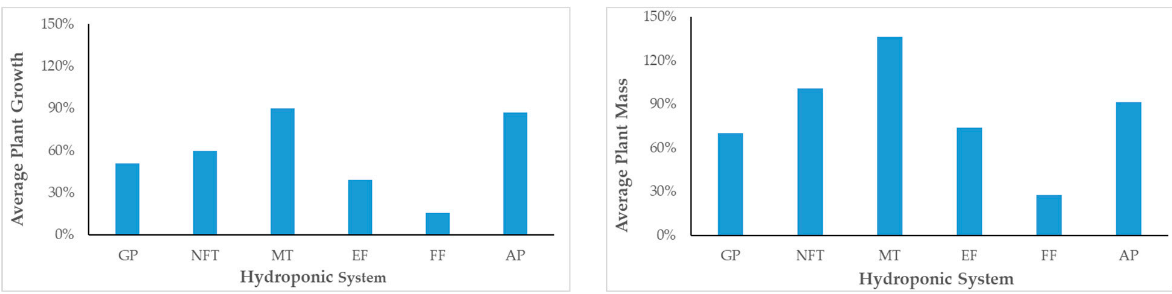


Figure 3. Total growth of the plants including root and body parts of the plants. Geyser pump (GP), nutrient film technique (NFT), misting (MT), ebb and flow (EF), full flow (FF), aeroponics (AP).



(**a**) (**b**)

Figure 4. Average growth as a measurement of length (**a**) and mass (**b**) as a percentage for each system across all experiments. Geyser pump (GP), nutrient film technique (NFT), misting (MT), ebb and flow (EF), full flow (FF), aeroponics (AP).

Overall, the MT and AP systems showed the greatest root growth (Table S1 and Figure 4). This was to be expected, due to the saturated environment that these systems create.

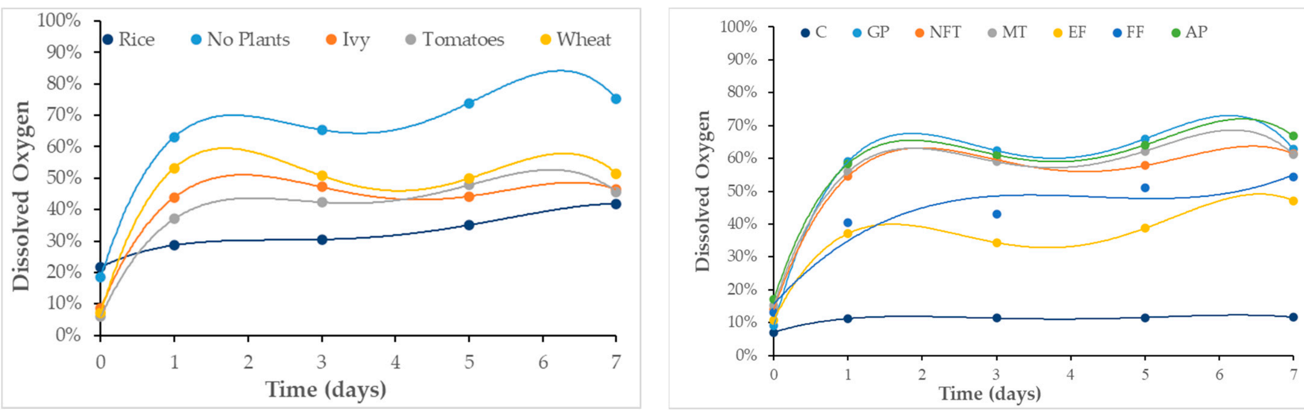
3.2. Water Parameters

Systems with and without plants showed slight variations in pH (Table S2), EC (Table S3), and TDS (Table S4) over time, but no significant difference was observed compared to the systems with plants. In addition, in all systems, a significant decrease in turbidity ($p \leq 0.001$; Table S5) and TSS ($p \leq 0.05$; Table S6) values was observed over time, with the following percentage reductions: turbidity (C: 98.99%, GP: 97.42%, NFT: 97.10%, MT: 97.25%, EF: 95.33%, FF: 96.74%, and AP: 96.1%), and TSS (C: 99.11%, GP: 99.15%, NFT: 99.15%, MT: 99.2%, EF: 98.95%, FF: 98.98%, and AP: 99.01%). Furthermore, it was observed that the run without plants showed little reduction in TOC (Table S7 and Figures S8 and S9) levels, while the run with plants exhibited a significant ($p \leq 0.05$) reduction (GP: 51.38%, NFT: 51.58%, MT: 60.79%, EF: 57.90%, FF: 63.49%, and AP: 69.08%). However, when comparing BOD (Figure S10) and COD (Figure S11) levels with and without plants, both showed a similar reduction.

In relation to nutrient analysis, ammonium (Table S8) levels decreased (GP: 96.16%, NFT: 96.16%, MT: 100%, EF: 100%, FF: 100%, and AP: 100%) significantly ($p \leq 0.05$ over time in all systems with plants, except for the control system (C), which remained relatively stable. However, removing plants from the systems did not result in a significant change in ammonium levels. Nitrite levels showed no significant changes (Table S9), and nitrate levels increased significantly ($p \leq 0.05$; Table S10) over time in all systems with plants compared to the control. Phosphate levels showed no significant (Table S11) difference.

3.3. Dissolved Oxygen

Initially, all hydroponic systems showed low DO levels (GP: 1.28 mg L^{-1}, NFT: 1.87 mg L^{-1}, MT: 2.01 mg L^{-1}, EF: 1.5 mg L^{-1}, FF: 1.80 mg L^{-1}, and AP: 2.27 mg L^{-1}), some below the recommended minimum (DO = 5 mg L^{-1}) [25]. To account for temperature variations, the theoretical saturation point corresponding to the recorded temperature was utilized due to the temperature-dependent nature of DO concentration. Figure 5a shows the percentage of the DO compared to the theoretical saturation point for all experiments, and Figure 5b shows the average DO for each hydroponic. In the beginning of the experiment, the theoretical saturation averaged between 10% and 20%. After the initial 24 h, the saturation levels increased in all systems as follows: GP (61.39%), NFT (59.44%), MT (60.43%), EF (40.37%), FF (48.70%), and AP (96.1%,), except for the control group (C) which remained at 11.88%, 1.61 mg L^{-1}. It was found that the rice runs showed noticeably lower average saturated oxygen.



(**a**) (**b**)

Figure 5. (**a**) Average DO throughout the experiment for all the systems averaged to the experiment run. (**b**) Average DO throughout the experiment for all the systems. Geyser pump (GP), nutrient film technique (NFT), misting (MT), ebb and flow (EF), full flow (FF), aeroponics (AP), control (C).

All the hydroponic systems started at a low level, some below the recommended minimum level of the DO, but quickly increased. In contrast, the C tended to have a level below the recommended level and at some points dropped close to the level of inhibition. The relationship between DO levels at the start, after 1 day, and at the end of the experiment was examined using a *t*-test, with significance set at $p \leq 0.05$ (Table 2).

Table 2. Average change of the DO for the first 24 h and the last 168 h of operation, and the *p*-values of the *t*-tests where $p \leq 0.05$ was considered significant.

		C	GP	NFT	MT	EF	FF	AP
First 24 h	Increase DO (%)	4.59	53.65	47.34	46.02	36.26	41.11	49.68
	t-test	0.13	$p \leq 0.05$	$p \leq 0.05$	$p \leq 0.05$	$p \leq 0.05$	$p \leq 0.05$	$p \leq 0.05$
168 h	Increase DO (%)	4.59	53.65	47.34	46.02	36.26	41.11	49.68
	t-test	0.16	$p \leq 0.05$	$p \leq 0.05$	$p \leq 0.05$	$p \leq 0.05$	$p \leq 0.05$	$p \leq 0.05$

Note: geyser pump (GP), nutrient film technique (NFT), misting (MT), ebb and flow (EF), full flow (FF), aeroponics (AP), control (C).

Table 2 highlights that all hydroponic systems experienced a significant ($p \leq 0.05$) increase in DO, with the GP system exhibiting the highest increase, followed by AP. FF and EF, characterized by their slow flow, showed a comparatively lower DO level and displayed the lowest growth. Surprisingly, the MT system demonstrated the greatest growth, despite not having the highest DO level, while the AP system, with the second-highest DO level, showed the next highest growth.

4. Discussion

After the first week of the tomato and at the end of the ivy experiments, a dense mat of roots created a strong anchor and a large surface area for biofilm growth [26].

The complex root system posed challenges during plant removal, often necessitating cutting, while measured data offer a comprehensive representation of substantial system-wide growth rather than specific plant growth.

Initial sewage samples exhibited high TSS and turbidity, but both decreased significantly within 48 h. After 72 h, levels were negligible. ANOVA confirmed a significant reduction ($p \leq 0.001$) in TSS and turbidity across all systems, including the control, which agrees with the literature [11,13,15]. Systems with plants showed significant ($p \leq 0.05$) reductions in TOC, as well as a decrease in ammonia levels (Tables S7 and S8). Ammonia oxidation to nitrite was faster in systems with plants. Adequate DO levels supported nitrification, resulting in decreased ammonium and increased nitrite and nitrate concentrations. It is expected that biofilms on roots aided in the nitrification process.

Water plays a critical role in plant survival, but it can hinder gas exchange and result in oxygen deficiency in the rhizosphere [27]. Optimal water and oxygen access is vital for plant growth, giving an advantage to MT and AP systems that allow access to gaseous oxygen form, which is preferred, as saturated soil has limited access [28]. Despite an overall increase in theoretical saturated oxygen, the rice experiment showed lower levels, suggesting potential influences from wastewater flow, root structure, biofilm, and temperature [29]. No significant correlation was found between plant species and DO. Further research is necessary to elucidate these factors and address the existing knowledge gap.

All systems started with a low DO; however, this increased rapidly over time, confirming the results for NFT found by Rababah [12]. Conversely, the C system consistently maintained lower DO levels, occasionally approaching inhibitory levels. Average DO across all systems was highest in the "no plants" experiment. No strong correlation was found between plant mass and DO levels. (Spearman correlation coefficient of 0.52, $p \leq 0.05$). Although the NFT system was anticipated to have the lowest DO levels, results indicated near saturation in the absence of plants. Contrary to expectations, the NFT system exhibited higher-than-anticipated DO levels, possibly due to turbulent water flow during return to the reservoir. Notably, the rice experiment displayed distinct patterns, with an initial decline in DO levels followed by a gradual increase throughout the entire duration compared to other runs.

Roots require oxygen for respiration unless they are flood-tolerant [30]. Initially, wastewater with low DO levels enters due to high BOD. However, hydroponic systems create turbulence and agitation, increasing the water's surface area exposed to air and facilitating oxygenation, leading to a significant increase in DO levels. The growth of oxidizing bacteria and decreased ammonium oxidation rates contribute to higher DO levels, observed in most systems except for the rice experiment, where continuous DO increase is attributed to oxygen transfer from aerial parts to roots, causing a leaching effect in the rhizosphere [31–33].

The DO concentration increases through surface interaction with the atmosphere [34]. In hydroponic systems, the water movement increases DO compared to stagnant water, such as in wetlands [35]. This increased availability of DO improved efficiency of biofilm oxidation of organic matter and increased survival chances for non-flood-tolerant plants. Successful plant growth of all systems affirms the stated advantages, while the reduced frequency of sewage–air interaction in the EF system led to lower DO.

The AP and MT systems, utilizing mist generation, exhibited enhanced root development. The observed rapid growth in the MT and AP systems resulted in the blockage and malfunction of the mister (Figure S12) and spray nozzle, respectively. In the MT system, root growth obstructed the outlet (Figure S6), leading to flow impeding and initial tomato run flooding. Extensive root growth in these systems was facilitated by the mist zone and the presence of air, especially oxygen (Figure 6).

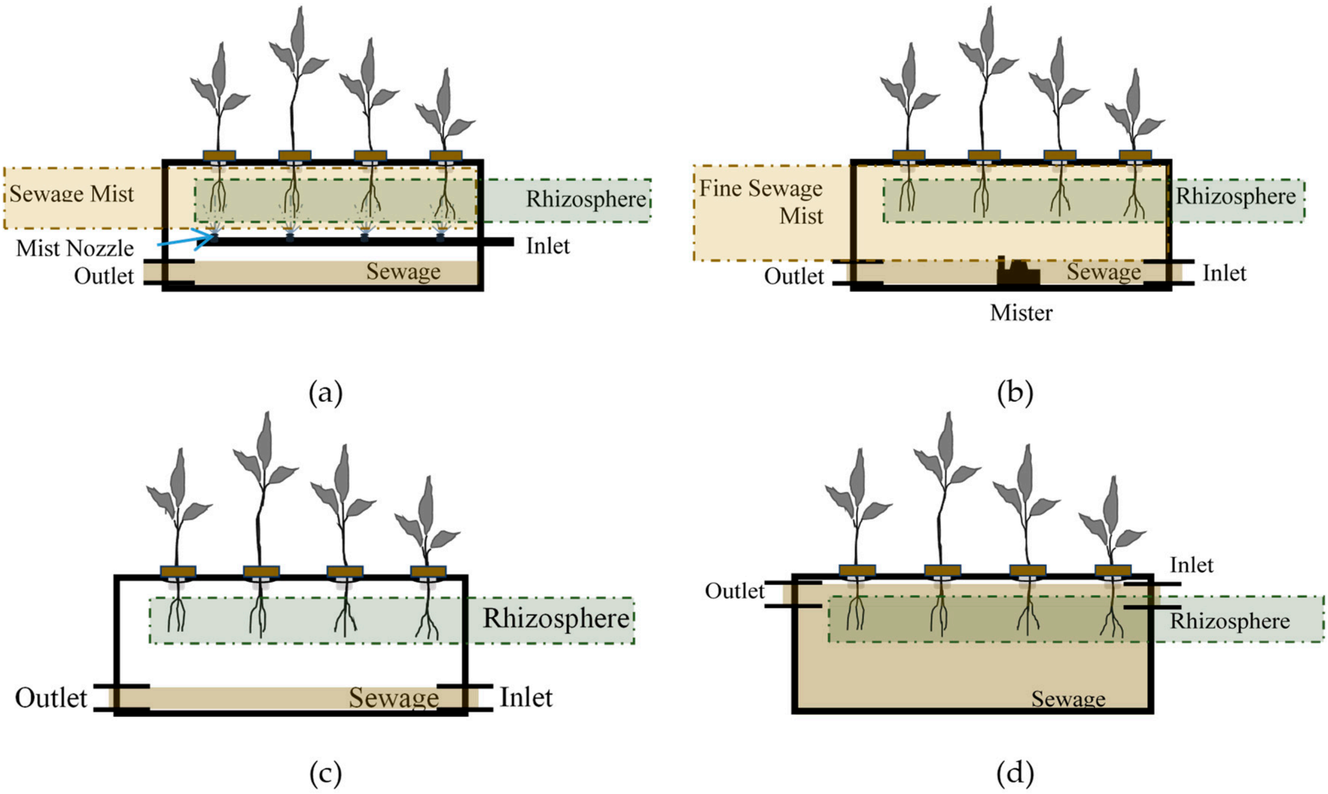


Figure 6. Schematics of the AP (**a**) and MT (**b**) systems showing the zone of moisture that encourage the growth of the rhizosphere. NFT (**c**) system showing the stream of sewage above the rhizosphere zone. A schematic of an FF (**d**) system showing that the rhizosphere was smothered in sewage restricting its access to oxygen.

The AP and MT systems create a mist zone that provides oxygen and nutrients to the roots and biofilm through microdroplets, ensuring proper moisture in the rhizosphere [36]. However, inadequate root length in our experiment hindered sewage access [28]. Conversely, the FF system showed excess moisture but limited oxygen, smothering the rhizosphere (Figure 6d). Rhizosphere narcosis (Figure S13) occurred in plant samples with minimal development, while the EF system differed from FF, allowing adjustment of oxygen-moisture ratio through drainage and flood cycles.

Ensuring adequate root volume is essential in hydroponic systems to facilitate maximize operation and promote biofilm development. Factors such as root architecture, dimension, surface area, and presence of root hairs influence biofilm formation and nutrient absorption [28,37]. Oxygen availability is critical for ideal root growth, with environments with abundance of both oxygen and moisture supporting the best results. AP and MT systems demonstrated uniform root development, while NFT systems concentrated roots at flow surfaces. In water-limited environments, oxygen availability plays a vital role by providing increased access to oxygen and nutrients for root uptake. The rhizosphere of the root system facilitates the breakdown of organic matter through the interaction of water droplets, leading to the production of ammonium and nitrate. These compounds, along with water and oxygen, are assimilated by the root system. In the design of a vertical urban farm, a vertical AP system is employed, incorporating an internal waterfall and fine droplets (Figure 7) to optimize this process.

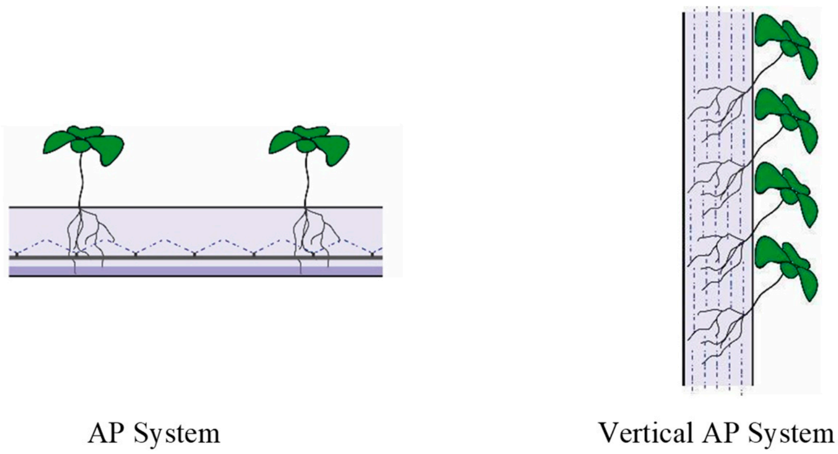


Figure 7. Utilizing a schematic inspired by the concept of plant growth on a waterfall, the AP hydronic system is transformed into a vertical AP system for vertical farming.

Our findings highlight the significance of oxygen availability in the degradation of organics and root health, thereby influencing plant growth and symbiotic biofilm formation. In constructed wetland systems, oxygen is scarce, but plants survive due to oxygen transport via aerenchyma, supporting some biofilm in the rhizosphere [5]. In contrast, hydroponic systems provide ample oxygen and DO, leading to accelerated aerobic oxidation of organics compared to anaerobic degradation [38].

5. Conclusions

In pursuit of these objectives, the experiments successfully demonstrated that oxygen availability is indeed a crucial factor for both plant growth and wastewater treatment in hydroponic systems. Results revealed that different hydroponic systems exhibit varying abilities to facilitate oxygen accessibility to the rhizosphere. The experiments conducted using different hydroponic systems, including GP, NFT, MT, EF, FF, and AP, demonstrated significant growth in plant mass and length. Results indicated minor variations in pH, EC, and TDS over time, while turbidity and TOC levels decreased significantly in the presence of plants. BOD and COD levels were reduced similarly with and without plants, while ammonium levels decreased, and nitrate levels increased significantly in plant systems. Moreover, notable increases in plant height and biomass were observed across all hydroponic systems, accompanied by higher levels of DO compared to the control. The hydroponic systems that provided a moist atmosphere through misting or aeroponics exhibited the greatest growth, confirming the importance of oxygen availability in the rhizosphere for plant growth and wastewater treatment. The MT and AP systems showed the greatest root growth due to their saturated environments. However, all systems exhibited overall growth and demonstrated the potential for plant cultivation in hydroponics. These findings underscore the importance of considering oxygenation strategies when designing hydroponic systems for optimal plant growth and wastewater treatment.

DO levels in the wastewater were a critical parameter for the success of the hydroponic systems. While initially, all systems showed low DO levels, they quickly increased over time. The NFT system, contrary to expectations, showed higher DO levels compared to other systems during experiments without plants. The control system consistently showed lower DO levels, sometimes dropping close to the inhibitory level. The rice experiment showed different patterns with a temporary dip in DO levels before gradually increasing.

Our results contribute to the development of sustainable urban vertical farming strategies by emphasizing the integration of ecological services and hydroponic systems for efficient wastewater treatment, resource recycling, and enhanced food production. Findings highlight the importance of optimizing access to both oxygen and nutrients in the rhizosphere to achieve maximum plant growth and wastewater treatment efficiency.

Further research is crucial to comprehend the impact of hydroponic methods on DO and plant–microorganism interactions. This will enhance engineering criteria, enabling more efficient and sustainable wastewater treatment and urban farming solutions, ultimately contributing to circular cities and environmental sustainability.

Supplementary Materials: The following supporting information can be downloaded at https://www.mdpi.com/article/10.3390/app13148032/s1. Figure S1. Diagrams of different hydroponic systems, NFT, DFT, aeroponic and fogponics. Figure S2. An illustration of the complete setup and the location of the different systems. Figure S3. An illustration of the proposed setup. The system that is gray is removed for illustrative purposes so that the system in color can be seen. The pipe is supported by its reservoir (colored) and that of the opposite system (gray). The pump pushed the water to the far end of the pipe. It flowed through the system via its specific method (illustrated is the MT system) and returned the other end to the reservoir by the return pipe. Figure S4. The six systems with tomato plants. Clearly, the fogponic system (MT) and the aeroponic system (AP) show the greatest growth. Figure S5. A photo of the experiment at the point when all tomato plants died. It was suspected that this could have been caused by high amounts of salts in the sewage seeping in from the sea. Figure S6. Photo of the outlet of the fogponic system, showing the extent of root growth, restricting the exit flow from the system. Figure S7. A photograph of the roots of an ivy plant. It can be seen that the roots have been cut, creating a log of roots. Table S1. Average lengths and mass over all the experiments, at the start and end, the percentage change in lengths and the p-value of the t-test where $p < 0.001$ were considered extremely significant. Table S2. Descriptive results of the pH for all the experiments and all the systems with plants and no plants. Table S3. Descriptive results of the conductivity for all the experiments and all the systems with plants and no plants. Table S4. Descriptive statistics and t-tests ($p \leq 0.05$ significant, $p \leq 0.01$ very significant, $p \leq 0.001$ extremely significant) of the TDS for all the experiments and all the systems with plants and without plants. Table S5. Descriptive statistics and t-tests ($p \leq 0.05$ significant, $p \leq 0.01$ very significant, $p \leq 0.001$ extremely significant) of the turbidity for all the experiments and all the systems with plants. Table S6. Descriptive statistics and t-tests ($p \leq 0.05$ significant, $p \leq 0.01$ very significant, $p \leq 0.001$ extremely significant) of the TSS for all the experiments and all the systems with plants and without plants. Table S7. Descriptive statistics and t-tests ($p \leq 0.05$ significant, $p \leq 0.01$ very significant, $p \leq 0.001$ extremely significant) of the TOC for all the experiments and all the systems with plants. Figure S8. Average reduction in TOC as a percentage change from start to finish in overall runs. Figure S9. Average reduction in TOC as a percentage change from start to finish of all systems per run. Figure S10. BOD from the beginning of each experiment in red and at the end of the experiment in blue. The percentage change is shown by the gray line. Figure S11. COD from the beginning of each experiment in red and at the end of the experiment in blue. The percentage change is shown by the gray line. Table S8. Descriptive statistics and *t*-tests ($p \leq 0.05$ significant, $p \leq 0.01$ very significant, $p \leq 0.001$ extremely significant) of the NH_4^+ for all the experiments and all the systems with plants and without plants. Table S9. Descriptive statistics and *t*-tests ($p \leq 0.05$ significant, $p \leq 0.01$ very significant, $p \leq 0.001$ extremely significant) of the NO_2^- for all the experiments and all the systems with plants and without plants. Table S10. Descriptive statistics and *t*-tests ($p \leq 0.05$ significant, $p \leq 0.01$ very significant, $p \leq 0.001$ extremely significant) of the NO_3^- for all the experiments and all the systems with plants. Table S11. Results for phosphate, descriptive statistics and *t*-tests ($p \leq 0.05$ significant, $p \leq 0.01$ very significant, $p \leq 0.001$ extremely significant) of the PO_4 for all the experiments and all the systems with plants and without plants. Figure S12. A photograph of the root system within the MT system. It can be seen that due to the excessive root system, the mister was smothered with the roots, hindering its functioning. Figure S13. A photo of the roots in the FF system showing that the roots did not develop to the extent as the roots in the other systems.

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