Hydroponic-Based Wastewater Treatment for Reuse: A Comparative Assessment of System Efficiency and Performance

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Abstract: This study assesses the performance and applicability of various pilot-scale hydroponic systems for the dual purpose of treating domestic wastewater and supporting agricultural food production. A comparative analysis of water quality improvement, based on removal efficiencies for TSS, TDS, BOD, COD, TN, and TP, identified the NFT and vertical gradual flow hydroponic systems as the most effective among the five systems evaluated. These systems demonstrated superior contaminant removal rates while promoting plant growth with targeted nutrient additions and addressing key challenges such as salinity and heavy metal accumulation. Key insights revealed improved crop productivity in specific contexts: faba beans and green peas thrived in NFT setups, while musk melons exhibited resilience to salinity levels up to 3000 ppm, making them suitable for saline regions. Additionally, the ability of certain crops to hyperaccumulate heavy metals offers a phytoremediation pathway, further enhancing the environmental benefits of hydroponic systems. Hydroponic setups were shown to produce high agricultural yields with minimal environmental impact, adaptable to both urban and rural contexts. A comprehensive SWOT analysis underscored the NFT system's significant strengths, including sustainability, cost-effectiveness, and environmental health benefits, while identifying minimal weaknesses and threats. Conversely, container and vertical flow systems demonstrated limited applicability due to higher operational challenges and fewer advantages. These findings support the NFT hydroponic system as a robust, scalable solution for wastewater treatment and agricultural production, with significant potential for continuous research, technological innovation, and broader application across diverse environmental and agricultural scenarios.

Keywords: Hydroponics, Decentralised wastewater treatment, Rural Areas, Effluent reuse, System Performance, Palestine.

1.INTRODUCTION

Hydroponic systems have emerged as innovative and sustainable solutions for wastewater treatment and reuse, addressing critical environmental challenges such as water scarcity and pollution. These systems utilize plants in a soilless medium, enabling direct nutrient uptake from wastewater while filtering out contaminants like nitrogen, phosphorus, and suspended solids. This dual-purpose process not only purifies wastewater but also produces nutrient-rich water suitable for agricultural and non-potable applications, aligning with circular economy principles to promote resource recovery and environmental sustainability [1].

Hydroponic-based water treatment systems have gained prominence as sustainable solutions for wastewater remediation, offering an efficient alternative for water reuse in resource-limited settings. Previous studies have demonstrated the potential of hydroponic systems to reduce pollutants like biochemical oxygen demand (BOD), chemical oxygen demand (COD), total suspended solids (TSS), and nitrogen compounds, thereby enhancing water quality for reuse purposes [2, 3].

Research highlights a range of hydroponic configurations—such as ebb-and-flow, drip irrigation, and nutrient film techniques (NFT)—each offering distinct advantages in nutrient removal, water efficiency, and maintenance simplicity. For instance, horizontal flow hydroponic systems have demonstrated up to 95% removal of suspended solids and a 91% reduction in biochemical oxygen demand (BOD), making treated wastewater viable for reuse in agriculture and landscaping [4]. Similarly, studies using Chrysanthemum cinerariaefolium in NFT systems achieved impressive pollutant removal rates, highlighting the effectiveness of plant-based remediation in hydroponics [5, 6].

The integration of hydroponic systems into municipal wastewater treatment presents a cost-effective alternative to traditional methods. By reducing maintenance and energy costs while simultaneously generating nutrient-enriched water for crop production, these systems support food security and environmental protection. Research indicates that the success of hydroponic wastewater treatment largely depends on its ability to continuously recycle wastewater for agricultural purposes while removing pollutants like nitrogen and phosphorus [7].

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Hydroponic wastewater systems address two critical global challenges: mitigating nutrient pollution and conserving water resources. Through treated water recycling, these systems reduce dependence on freshwater sources, offering a sustainable approach to wastewater management, particularly in water-stressed regions. Advances in technology, including the incorporation of Internet of Things (IoT) sensors and machine learning, have further enhanced the monitoring and efficiency of hydroponic systems, allowing real-time optimization of water quality and treatment processes [8].

Traditional wastewater treatment methods are often resource-intensive, requiring significant infrastructure, energy, and chemicals. In contrast, hydroponic systems leverage natural biological processes to achieve pollutant removal, providing an environmentally friendly and scalable alternative. For example, closed hydroponic systems prevent nutrient runoff and groundwater contamination, making them ideal for regions where water conservation is essential [9].

Studies have consistently demonstrated the effectiveness of hydroponics in removing a wide range of pollutants, including heavy metals, nitrogen, phosphorus, and pathogens. For instance, up-flow biological filters in hydroponic systems have achieved up to 90% nitrogen removal, showcasing their potential for high-efficiency wastewater treatment [10]. Furthermore, the Internet of Things (IoT) integration with hydroponic systems has enhanced treatment accuracy by enabling precise control of parameters such as nutrient levels and pH, reducing maintenance costs and extending system lifespans [8].

Hydroponic wastewater treatment systems not only purify water but also produce high-quality effluent suitable for reuse. By incorporating plant species with high nutrient and heavy metal uptake rates, these systems have consistently demonstrated pollutant removal levels that meet or exceed reuse standards. For example, Chrysanthemum cinerariaefolium in hydroponic systems removed 95% of suspended solids and achieved a 91% BOD reduction within 48 hours [5].

In summary, hydroponic-based wastewater treatment offers a sustainable alternative to conventional methods, combining efficiency, scalability, and resource recovery. By contributing to water security and environmental protection, hydroponic systems provide innovative solutions to global challenges such as water scarcity and pollution.

This paper will evaluate various hydroponic techniques treating contaminated water and/or wastewater, comparing their efficiency, comparing the efficiency of different plant species, design configurations, and potential for reuse to identify optimal solutions for diverse environmental and operational needs.

2. BACKGROUND AND RATIONALE FOR HYDROPONIC WASTEWATER TREATMENT

2.1. Background

Hydroponics, a soil-less method of naturally growing plants, has emerged as a cornerstone of sustainable agriculture. By directly delivering nutrients to plant roots through water, hydroponics maximizes efficiency in nutrient and water usage while enabling controlled growth conditions. This approach has gained popularity globally for its potential to address challenges like declining arable land, water scarcity, and the need for sustainable urban farming solutions [1].

However, hydroponic systems generate nutrient-rich wastewater as a by-product of their operations. This wastewater often contains dissolved nutrients such as nitrogen, phosphorus, and potassium, along with other elements, salts, and organic residues. If not recirculated within the system, the discharge of this effluent into natural water systems can lead to environmental challenges such as eutrophication causing algal blooms and oxygen depletion [11].

Traditional methods of wastewater treatment, whether aerobic or anaerobic, have been essential in managing urban and rural wastewater. However, these systems come with inherent challenges, including high energy demands, infrastructure requirements, and significant management needs. Aerobic treatment systems, such as activated sludge processes, rely on continuous aeration to supply oxygen for the microbial degradation of organic matter. This process is energy-intensive, with aeration accounting for up to 60% of the total energy consumption of wastewater treatment plants [12]. Anaerobic systems, though less energy-intensive, require controlled environments to maintain optimal conditions for microorganisms, which can increase operational complexity [13]. Key insights of traditional treatment systems include:

- Infrastructure and Space Requirements: Both aerobic and anaerobic systems necessitate large infrastructure, including tanks, pipelines, aerators, and digesters, often requiring significant land area. For example, anaerobic digesters need sealed tanks to contain biogas production, while aerobic systems require expansive aeration basins. These spatial demands can pose challenges in urban areas where land availability is limited [14].

- Operational and Financial Strain on Municipalities: Municipalities face considerable financial and managerial challenges in operating and maintaining traditional wastewater treatment plants:
- High Costs: Both the capital investment for infrastructure development and the recurring operational costs, such as energy and chemicals, represent a significant economic burden.
- Maintenance and Skilled Workforce: Regular maintenance and a skilled workforce are required to ensure efficient operation, which can be a constraint in regions with limited technical expertise.
- Aging Systems: Aging infrastructure in many municipalities results in inefficiencies and increases the risk of untreated wastewater being discharged into the environment [15].
- Environmental Concerns: Traditional systems can produce high volumes of waste sludge, which require further treatment or disposal, adding to environmental and operational burdens. Additionally, these systems are often vulnerable to fluctuations in wastewater flow and composition, such as during storm events, which can compromise treatment efficiency [16].

Traditional wastewater treatment systems, while effective, pose challenges related to energy consumption, infrastructure requirements, and management demands. These limitations highlight the need for alternative approaches that are more energy-efficient, space-saving, and sustainable, such as integrating wastewater treatment with resource recovery systems like hydroponics [11].

Domestic wastewater, a separate but related resource, also contains significant amounts of organic matter and nutrients. Historically considered waste, wastewater is increasingly viewed as a valuable resource for nutrient recovery and water reuse. Treating this wastewater through hydroponic systems combines agriculture with wastewater management, creating a closed-loop approach that aligns with circular economy principles [17].

2.2. Rationale

The integration of hydroponic systems with wastewater treatment provides a compelling solution to address critical environmental and agricultural challenges and a sustainable approach to resource management. This dual-purpose approach leverages the nutrient content of wastewater to nourish plants, while simultaneously treating the wastewater to reduce pollutants. The key advantages of this system include:

- Water Conservation: Global freshwater resources are under significant pressure due to urbanization, industrialization, and agriculture. Using treated wastewater in hydroponic systems reduces reliance on freshwater resources, promoting sustainability in water management [18].
- Nutrient Recovery and Circular Economy: wastewater contains valuable nutrients that are often lost in traditional treatment processes. By integrating these nutrients into hydroponic systems, they are repurposed for agricultural production, reducing the need for synthetic fertilizers, which are resource-intensive and environmentally harmful to produce [19].
- Environmental Protection: Untreated or poorly managed wastewater discharge is a major contributor to water pollution. Hydroponic treatment systems reduce nutrient loads and organic pollutants in wastewater, mitigating risks such as eutrophication and groundwater contamination [20].
- Enhanced Urban Agriculture: As urban areas expand, space for traditional farming becomes limited. Hydroponic wastewater treatment systems can be designed for compact urban settings, enabling local food production and reducing food miles. This is particularly relevant in urban and peri-urban environments, where access to fresh produce is often constrained [21].
- Economic Viability: By converting wastewater into a resource for hydroponic farming, municipalities and private entities can reduce

wastewater treatment costs while generating revenue from crop production. Additionally, year-round operation of hydroponic systems increases the economic viability compared to seasonal traditional farming [22].

- Food Security and Climate Resilience: Hydroponic systems integrated with wastewater treatment can produce vegetables and other crops sustainably, contributing to food security in areas affected by climate change, water scarcity, or limited arable land. By adapting to variable climates, these systems are crucial for resilient agricultural practices [23].

3. HYDROPONIC SYSTEM DESIGNS, EXPERIMENTAL SETUP AND PROCEDURES

The following sub-sections summarize each hydroponic research study, including its title, research question, and system design. The selection criteria for the chosen research study s were as follows:

- Institutional Affiliation: All studies were conducted at An-Najah National University under the supervision of the author.

- Focus Area: The studies specifically addressed the field of hydroponic wastewater or contaminated water treatment.

- System Diversity: Each study utilized a unique hydroponic system design, showcasing a variety of approaches.

- Plant Variability: A range of plant species was employed across the study s to evaluate growth performance and treatment efficiency within the hydroponic systems.

3.1. Performance Of Hydroponic Wastewater System As Decentralized Wastewater Treatment And Reuse For Communities [4, 24]

This study, conducted from 2007 to 2012 by the Water and Environmental Studies Institute at An-Najah National University in Palestine, in which the author participated as a researcher, tested two hydroponic systems for decentralized wastewater treatment and reuse in rural and urban settings. The study aimed to assess the performance of hydroponic systems—specifically, hydroponic barrels and channels—as efficient, decentralized wastewater solutions for local communities in Palestine.

The pilot plant was located on An-Najah National University's campus and consisted of several key components: a primary settling tank, a greenhouse containing the hydroponic system, a final settling tank, and an area designated for reusing the treated effluent. The primary settling tank, which could hold approximately 13 m³ of wastewater, was designed to balance fluctuating wastewater inflows typical in small communities. The tank was elevated to allow gravity-driven flow into the greenhouse, where the hydroponic system was housed (see Figure **1**).

Within the greenhouse, hydroponic treatment was executed using two setups: hydroponic barrels and channels. The channels were constructed from steel, each measuring 27 m in length, 22 cm in width, and 35 cm in height (see Figure **3**). They were divided longitudinally into two sections, resulting in a total of six channels.

The barrels and channels were partially filled with a custom media mixture (gravel, wood sawdust, and agricultural sand in a 2:1:1 ratio by volume), which provided a moist environment suitable for plant root development. Three groups of five barrels were used. The channels, constructed from anti-corrosion steel and organized in double rows, allowed for a comparative study of wastewater treatment efficacy between media-filled and media-free setups. These design choices sought to optimize nutrient absorption and pollutant removal through plant roots and the supporting media, demonstrating hydroponics as a practical and sustainable option for local wastewater management and water reuse.

A steel tank coated with an anti-corrosion layer was used to supply settled wastewater to the channels and the barrels. The tank had a capacity of 13 m³ (see Figure **1**).

Effluent was then directed to an open, eastward area intended for reuse (width = 8.5 m and length = 150 m, see Figures **1**,**2**, and **3**). This reuse zone, covered with agricultural sand (15-30 cm of agricultural sand) and designed to eventually support grass, demonstrated how treated water could be repurposed sustainably, highlighting the study 's potential for eco-friendly wastewater treatment and community water reuse.

A group of plants were tested in the hydroponic system. The cropping started by the start of the second week of June 2007, and seedlings were purchased from a local nursery. The plants were replaced after the

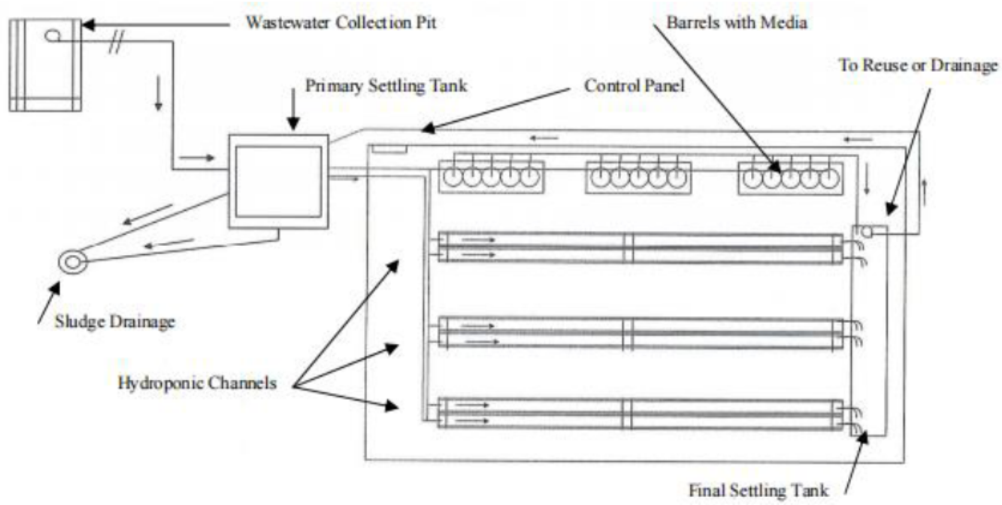

Figure 1: Schematic of hydroponic pilot plant.

growing season. Up to date and for the period of over three years the following plants were tested:

- Vegetables: Winter squash, green beans, sweet corn, eggplants, and cherry tomatoes
- Various cut flowers: Tagetes erecta, Asarina procumbens, Alonsoa warscewiczii,
- Calendula officinalis Gitano Mix, Arctotis hybrida
- Trees: Citrus and olives
- Herbs: Rosemary

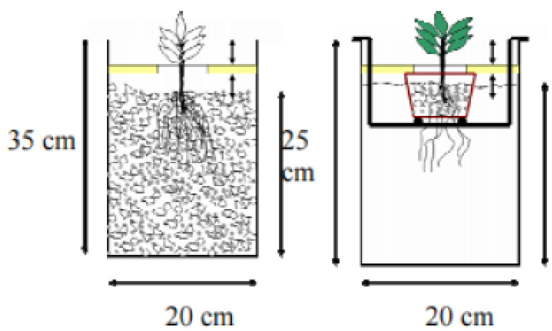

Figure 2: Schematic of hydroponic open channels.

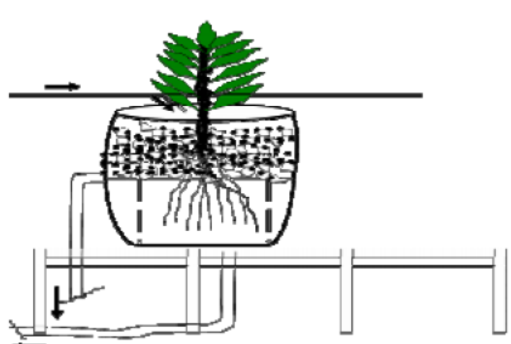

Figure 3: Schematic of hydroponic barrels.

3.2. Evaluation of Salinity and Selected Trace Metals on Muskmelon Growth, Yield, and Uptake in a Horizontal Hydroponic System [25]

The experiments were conducted in a greenhouse located on the new campus of An-Najah National University. The greenhouse was constructed with a galvanized steel frame and covered with a durable plastic layer. The dimensions of the greenhouse were 36 m in length, 8.5 m in width, and 5.5 m in height. The hydroponic system used in this study comprised three hydroponic channels within the system described in section 3.1, a water tank, an aeration tank, and a settling tank (see Figure **1** and **2**):

The three hydroponic channels were utilized as follows:

- Salinity Experiment (Channel 1): Divided into three sections, each 9 m in length and containing 20 seedlings. Sections were treated with NaCl concentrations of 1000, 3000, and 7000 ppm, respectively.
- Trace Metal Experiment (Channel 2): Divided into two sections, each 13.5 m in length and containing 30 seedlings.
- Sections were treated with concentrations of 0.1 ppm and 0.2 ppm of Zn, Cr, Cu, and Cd, respectively.
- Control (Channel 3): Treated with tap water only. Divided into two sections, each 13.5 m in length, with 30 seedlings in each section.

Melon seedlings were sourced from a local nursery and were free from viral, fungal, or bacterial infections.

Seedlings were 11–14 cm tall with 8–12 healthy, green leaves. The seedlings were spaced 45 cm apart within all channels.

Seedlings were grown on nutrient-supplemented media for 45 days before the application of salinity and trace metal treatments. Nutrient supplements were added weekly throughout the four-month growth period.

Data on plant height and leaf count were recorded for each seedling across all treatments before the application of salinity or trace metals. Growth was monitored weekly, and final data were collected at the end of the four-month study period.

At harvest, plants were analyzed for biomass and chemical composition.

Water quality parameters were conducted according to standard methods for examination of water and wastewater. Trace Metal Analysis were made according to the protocol by Chaturvedi and Sankar (2006) [26].

3.3. Effects of Nutrients and Salinity on Yields, Growth, and Nutrients distribution of Faba Beans Grown in a Nutrient Film Techniques (NFT) Hydroponics System [27, 28]

This study evaluated the performance of a NFT hydroponic wastewater treatment system to determine its feasibility as a decentralized solution for wastewater treatment and reuse in rural and urban Palestinian communities. It tested a piped hydroponic system using six treatment groups with different nutrient and salinity levels to assess the impact on three faba bean varieties: Artasi, Baladi, and Ispani(see Figure **4**). The experiment divided plants into six treatment groups, each replicated across three lines for a total of four replicates per line. The six treatments were: Control (TRT0):0 NaCl, (TRT1 - TRT3): Included 25%, 100%, and 300% of Cooper nutrient solution, (TRT4 and TRT5): 4.68 ds/m and 7.8 ds/m NaCl solutions.

A PVC-based hydroponic setup with six reservoirs supplied nutrient and saline solutions through 2-meter-long, 6-inch PVC pipes, each holding four replicate plants. The pipes were drilled to secure plastic pots with plants, with a drain at the base to recycle water back to the reservoirs. The nutrient delivery system used an internal spray tube and a pump to circulate the solutions (See Figure **4**).

Following germination in peat moss, the seedlings were transferred to hydroponic pots. Figure is a picture of the hydroponic system in operation. For acclimation, tap water was circulated initially, replaced by nutrient solutions three times daily afterward. Evaporative and transpired water was periodically replenished. Plant support, daily observations, and root measurements ensured optimal growth conditions.

Figure 4: Picture of the NFT hydroponic system in operation.

3.4. Evaluation of the Impacts of Selected Trace Elements and Salinity on the Growth, Yield, and Uptake of Bell Pepper Grown Under Sequential Vertical Flow Hydroponic Conditions [29]

This study examined the effects of salinity and trace element uptake on the growth, yield, and nutrient absorption of bell peppers (Capsicum annuum) cultivated in a sequential vertical flow hydroponic system. The experimental setup consisted of 26 perforated containers arranged in five rows, with three rows treated with varying concentrations of saline solutions (S1: 1000 mg/L, S2: 3003 mg/L, and S3: 7000 mg/L NaCl) and one row exposed to trace element treatments (0.2 mg/L of cadmium, copper, chromium, and zinc). A control row, irrigated with tap water, was also included. Each container housed five plants evenly distributed to ensure uniform growth conditions.

The system was configured to allow water to flow vertically, with percolated water from upper containers irrigating lower ones. Plants were irrigated daily with 3–4 liters of water, while saline or trace element solutions were added weekly. Excess water was manually transferred between containers to ensure consistent recycling. The growing media consisted of a gravel base, topped with 10 cm of peat moss and 5 cm of sand mixed with smaller gravel. Growth parameters, including stem length, leaf count, and fruit development, were measured weekly. Percolated water was analyzed for pH, electrical conductivity (EC), and dissolved trace metals (see Figures **5** and **6**).

Figure 5: Planting plants in containers.

Figure 6: Tray hydroponic system in operation.

The experiment was conducted from late May to late July in a rooftop garden in Jammaein, south of Nablus, a region with a Mediterranean climate characterized by hot, dry summers and mild, rainy winters. Bell pepper seedlings, measuring 5–6 cm in height with 5–7 leaves, were transplanted into the containers. At the end of the six-week period, plants were harvested, and samples were analyzed for fresh and dry biomass. Root, stem, and leaf samples were dried, weighed, and tested for trace element and salinity content.

3.5. Effects of Salinity, Nutrients and Heavy Metals on Growth, Yield and Uptake of Pea in Piped Hydroponics [30, 31]

This study investigated the effects of salinity, nutrients, and heavy metals on the growth, yield, and nutrient uptake of green peas (Pisum sativum) cultivated in a piped hydroponic system. The experimental setup consisted of six growth lines, each comprising five plastic pipes with dimensions of 1.5 meters in length and 6 inches in diameter. Each pipe housed four seedlings placed in 3.5-inch holes. Internal spray lines, nozzle sprayers, and drainage systems ensured efficient irrigation and nutrient delivery (Figure **7**). Green pea seeds, sourced from a local agricultural market, were initially germinated in organic soil (ECO TERRA) for two weeks until seedlings reached 5–7 cm in height. The seedlings were then transplanted into 4-inch plastic pots filled with 0.5-inch tuff stones and placed into the hydroponic system. Seedlings were supported with yarn and ropes to maintain a vertical growth position. After one week of initial irrigation with tap water, a nutrient solution was introduced.

Figure7: Picture of NFT hydroponic system in operation.

The hydroponic growth system (HGS) was constructed with pipes mounted on a 1-meter-high wooden stand. Irrigation water was recirculated using pumps connected to 120-liter plastic drums, which supplied nutrient solutions to the pipes. Excess solutions drained back into the drums for recycling. Nutrient and salinity treatments were applied across six experimental lines with varying compositions, including salinity levels of 750, 1500, and 3750 ppm and trace elements such as zinc sulfate, copper sulfate, and iron-EDTA. Line 3, irrigated with freshwater and 750 ppm salinity, served as the control.

Growth metrics were recorded weekly, including seedling length, leaf area (measured with graph paper), and counts of leaves, pods, and flowers categorized into small, medium, and large sizes. At the end of the two-month growing season, plants were harvested and separated into leaves, stems, pods, and roots.

Fresh and dry weights of these parts were measured, and the relative water content (RWC) was calculated. Dried plant samples were subjected to further analysis for salinity, nutrients, and heavy metals. The experimental design followed a Completely Randomized Design (CRD) with five pipes and four replicates per pipe.

3.6. Evaluation of a Gradual Hydroponic System for Decentralized Wastewater Treatment and Reuse in Rural Areas of Palestine [32, 33]

This study evaluated the use of a gradual hydroponic system for decentralized wastewater treatment and reuse, conducted at An-Najah University's new campus. Wastewater from the university's scientific faculties was collected into a storage tank and pumped to a 15 m³ elevated tank to regulate flow. From this tank, wastewater was distributed to five large containers (45 cm in diameter and 90 cm in height), each supplying a row of five barrels configured as plant growth cells. The barrels, arranged on a stepped metal frame, enabled wastewater to flow gravitationally through the system without additional pumping (Figures **8** and **9**).

Each barrel was filled with a layered media profile totaling 50 cm:

- Drainage Layer (13 cm): Large aggregates (10–15 cm) to facilitate drainage and prevent clogging.
- Intermediate Layer (27 cm): Medium aggregates (1–2 cm).
- Top Layer (10 cm): Medium aggregates mixed with sand (3:1 ratio), enhancing filtration.

The wastewater level was maintained at 40 cm, leaving a 10 cm gap for aeration (Figure **3**). The system operated with a flow rate of 12 mL/min (17.28 L/day), achieving a hydraulic loading rate of 0.11 m³/m²·day and a total hydraulic retention time (HRT) of six days. Each barrel was equipped with a 1.5-inch perforated pipe (60 cm length) for wastewater level monitoring and aeration. High porosity (45%) in the system improved durability, prevented clogging, enhanced treatment capacity, and maintained sufficient aeration for effective removal of biological oxygen demand (BOD) and total nitrogen (TN).

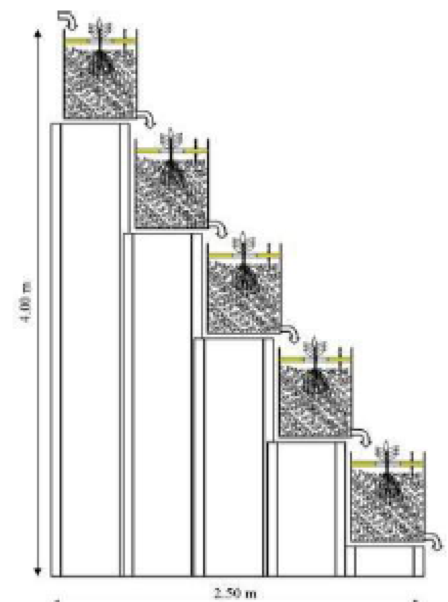

Figure 8: Schematic of the gradual hydroponic system.

Figure 9: Picture of gradual hydroponic system.

Five seasonal crops—corn broom, alfalfa, sweet corn, barley, and sunflower—were grown in the system, with each crop assigned to a row of five barrels representing five sequential treatment stages. Wastewater flowed vertically from the top to the bottom of each row, with each barrel holding 25.6 L of wastewater. The HRT was 1.5 days per barrel, adding up to six days across all five barrels.

Wastewater quality was monitored at the system's inlet and outlet throughout the six-month experimental period. Parameters included total suspended solids (TSS), total dissolved solids (TDS), BOD, chemical oxygen demand (COD), nitrogen (N), and chlorides (Cl). Samples were collected in glass bottles at 10:00 a.m. and analyzed within 30 minutes using standard methods for water and wastewater testing [7].

The atmospheric temperature averaged 32±4°C, while wastewater temperature was maintained at 24±2°C. To isolate the natural effects of the hydroponic system and wastewater on plant growth and uptake, no chemical nutrients were added during the experiment. This setup demonstrated the potential for decentralized wastewater treatment and reuse in rural areas, utilizing hydroponics as a sustainable and efficient approach.

3.7. Evaluation of Yield and Energy Budget of Muskmelon Grown in a Horizontal Hydroponic System Under Different Nutrient Inputs [34]

This study aimed to evaluate the yield and nutrient uptake of muskmelon grown in a horizontal hydroponic system under varying nutrient regimes. The system was designed and managed featuring a setup described as shown in Figure **1**.

On March 26, 2013, 210 muskmelon seedlings (6–7 cm in height, with 3–4 leaves) were planted in the four canals, with 52–53 seedlings per canal, spaced 50 cm apart.

Nutrient addition began on April 28, 2013. The three nutrient-treated canals received different levels of fertilizers: Canal 1: 1/4 strength NPK, Canal 2: Full-strength NPK, Canal 3: Full-strength NPK with 1000 ppm sodium chloride (NaCl), Canal 4: Control (no fertilizers added).

Before and after fertilization, plant growth metrics (height, number of leaves, and number of fruits) were recorded weekly. At harvest, muskmelons were evaluated for yield (kg fruit/plant), nutrient uptake, and energy budget. Nutrient analysis was performed on both root and aerial parts (stems, leaves, and fruit). Samples were oven-dried at 550°C for 8 hours, and nutrient concentrations were determined in the laboratory according to standard methods for examination of water and wastewater [35].

Mature muskmelons were harvested and weighed (kg fruit/plant). Ten milliliters of fruit pulp were extracted from 20 random samples to measure sugar concentration using a handheld refractometer (see Figure **10** and **11**).

4. COMPARISONS, IMPLICATIONS, AND APPLICATIONS

The results of the five pilot hydroponic systems were reviewed and were used in the following two section.

4.1. Water Quality Performances of Various Hydroponic Systems

The above listed results agree with those published in the literature [37-40].

Table 1: Contaminants Removal Efficiencies for Various Hydroponic Systems

Hydroponic System	Contaminant Removal Efficiency [%]					
	TSS	TDS	BOD	COD	TN	TP
Barrels	82.3	25.5	24.7	55.1	34	37
Channels	82.3	0.1-27.8	30.8	66.5	34	37
Vertical gradual flow	90-97	20-45	94-97	80-89	63-65	40-70
NFT	85	30	70-90	80-90	50-70	50-80
Sequential Vertical Tray	80-95	10-30	80	70-80	50-70	40-60
Effluent Standards, mg/l [36]	<30	500-1000	20-30	50-100	10-15	<1

Figure 10: Muskmelon planted in the hydroponic channel.

Figure 11: Muskmelon growth in hydroponic channels.

The following represent the key insights drawn from the above Table:

- Hydroponic systems, particularly NFT and vertical gradual flow designs, achieve moderate to high removal efficiencies for key effluent wastewater parameters.
- Comparison of total nitrogen and phosphorus removal rates across systems indicate similarities although NFT and vertical gradual systems were notably higher than other systems.
- Organics, BOD and COD, removal rates in the NFT and vertical gradual systems were higher than other systems while barrels and channels were the lowest.
- Suspended solids removal in all systems was high while dissolved solids removal was marginal.
- Overall, the NFT hydroponic system represent and proved to be better than other listed systems in effluent water quality improvement.

The initial design, whether in the form of hydroponic barrels or channels, NFT, Trays, or vertical sequential flow, was unable to produce an effluent that met accepted standards. However, it proved effective in removing TSS and organics at high levels.

4.2. SWOT Analysis

A SWOT analysis for a hydroponic system that treats wastewater and grows vegetative plants. I used the numerical scale rating system for SWOT analysis because of its precision and ability to provide clear differentiation between SWOT items, is straightforward to quantify and compare, and its intuitive structure makes it user-friendly. This approach aligns with best practices outlined by Streiner & Norman (2008) and Couper *et al*. (2001)[41,42]. SWOT items were rated on a 1 to 10 scale, with the following interpretations:

For strengths and opportunities:

- 9–10: Excellent or highly favorable factors (*e.g*., unique competitive advantages or high-impact opportunities).
- 7–8: Important but slightly less excellent or critical factors.
- 5–6: Moderate relevance.
- Below 5: Minor or insignificant strengths/opportunities.
- For weaknesses and threats:
- 9–10: Significant weaknesses or critical threats that could severely affect performance.
- 7–8: Moderate importance, needing attention but not immediately critical.
- 5–6: Low impact or less urgent.
- Below 5: Negligible weaknesses or threats.

The container and vertical flow hydroponic systems exhibit fewer strengths and opportunities while presenting the most significant weaknesses and threats compared to the other five systems evaluated. Consequently, these systems are not broadly recommended for nationwide adoption (see Tables **2**-**5**). However, they may serve as viable alternatives in specific locations that fulfill the necessary conditions for their operation. To implement such systems effectively, additional efforts are required to build technical knowledge, refine practices, and ensure proper management.

The NFT (Nutrient Film Technique) hydroponic system demonstrated the highest strengths and opportunities among the five systems analyzed. It outperformed others in areas such as sustainability, yield and food production, water conservation, nutrient recycling (reducing the need for synthetic fertilizers), and cost-effectiveness. Additionally, it posed minimal challenges in maintenance and exhibited lower risks related to hygienic contamination and environmental impacts, making it a highly viable and efficient option for hydroponic farming. This system's viability for continuous research, development, and technological upgrades further enhances its potential, making it a recommended choice for both small-scale and large-scale hydroponic farming initiatives.

The hydroponic barrel and channel systems, the last two evaluated, exhibited moderate performance across all SWOT analysis dimensions: strengths, opportunities, weaknesses, and threats. Both systems were operationally effective; however, they have distinct applications. The barrel hydroponic system is compact and best suited for small-scale setups, such as home gardens or private projects, due to its discrete nature. Conversely, the channel system offers scalability for larger operations but is prone to media clogging over time. These systems are most effective under specific, well-studied conditions, making them ideal for small private farms and specialized project s with proper management and maintenance.

5. SYNTHESIS OF INSIGHTS AND FUTURE TRENDS

Based on the above presentation and author's readings, hydroponics, as a modern agricultural innovation, opens a new frontier in science, enabling increased crop production for food, fodder, and ornamental purposes while enhancing yield quality. Hydroponic wastewater treatment is an evolving field that integrates plant-based systems for the remediation of wastewater. Choosing the most suitable hydroponic system depends on balancing cost, maintenance, resource efficiency, and production goals. Further research and innovation can address current limitations, particularly in nutrient delivery, system scalability, and energy efficiency, ensuring hydroponic farming's role in sustainable agriculture continues to grow.

The following advancements are the potential future improvements and innovations in hydroponic wastewater treatment:

- Integration of hydroponic with Bioelectrochemical Systems: Combining hydroponic systems with bioelectrochemical technologies, such as microbial fuel cells [43-45], or vermifiltration, can enhance pollutant degradation and energy recovery. This integration offers a dual benefit of wastewater treatment and sustainable energy production [46].

- Advanced Sensor Technologies and Real-Time Monitoring: Implementing sophisticated sensors and real-time data analytics can optimize nutrient delivery and monitor system health, leading to more efficient wastewater treatment processes. Future hydroponic wastewater systems are expected to incorporate Internet of Things (IoT) technology for real-time monitoring and control. Sensors will track water quality parameters such as pH, nutrient levels, and contaminants, enabling automated adjustments to maintain optimal conditions. This will increase efficiency and reduce the need for manual intervention [47].

- Utilization of Indigenous Microbial Consortia: Employing native microbial communities that naturally develop in hydroponic farm wastewater can improve treatment efficiency by enhancing nutrient removal and reducing harmful compounds.

- Development of Low-Cost Hydroponic Technologies: Creating affordable hydroponic systems such as the NFT, barrel, or open channel , and stepwise systems can make wastewater treatment more accessible, especially in developing regions. This approach can reduce reliance on human labor and lower both startup and operational costs.

Table 2: SWOT Analysis of Five Pilot Hydroponic Systems: Strengths

Hydroponic System Type / SWOT Titles	Barrels	Channels	NFT	Containers	Vertical Flow
Strengths					
Sustainability:	5	6	9	5	5
Resource Efficiency:	8	8	9	5	5
Nutrient Recovery and Recycling:	8	8	8	8	8
Economic Benefits:	6	7	9	5	56
Innovative Technology:	7	7	9	6	6
Localized Food Production:	7	7	9	5	5
Year-Round agricultural Production	7	8	9	6	6
Compact, Versatile, and Scalable Design:	8	8	9	7	7
Environmental Health and Hygiene Benefits:	8	8	9	7	7
Efficient Water Utilization and Conservation:	8	8	9	7	7
Government policy Support	5	5	5	5	5
Public Perception and Acceptance:	7	8	9	5	5
Operational Sensitivity:	8	8	9	6	6
Space and Urban Constraints:	7	7	7	4	5
Climate change	5	5	5	5	5
Complex Management	8	8	8	5	5
Regulatory and Economic Barriers and Hurdles:	7	7	9	5	5
Environmental and Health Risks and Challenges:	8	8	9	7	7
Market Acceptance and Competition Uncertainty Issues:	7	7	7	7	7
System Failures and Risks:	8	8	9	7	7
Energy and Resource Dependency:	8	8	8	8	8
Competition with Conventional Treatment and Reuse Systems	5	5	9	3	3
Subtotal	**91**	**92**	**103**	**74**	**75**

Table 3: SWOT Analysis of Five Pilot Hydroponic Systems: Opportunities

Hydroponic System Type / SWOT Titles	Barrels	Channels	NFT	Containers	Vertical Flow
Opportunities					
Rising Demand for Sustainability and Economy Solutions:	5	7	9	4	4
Urban Farming Expansion:	8	8	9	5	5
Government and International Support:	5	5	5	5	5
Innovation, Research and Development:	6	6	9	5	5
Growing Awareness of Water Scarcity:	7	7	7	7	7
Diverse Applications:	7	7	7	7	7
Urban Agriculture Trends:	8	6	8	7	7
Government Incentives:	4	4	8	4	4

Scalability:	7	7	9	5	5
Circular Economy Integration	6	6	8	5	5
Product yield and Quality	7	7	9	6	6
Subtotal	**70**	**70**	**88**	**60**	**60**

Table 4: SWOT Analysis of Five Pilot Hydroponic Systems: Weaknesses

Hydroponic System Type / **SWOT Titles**	**Barrels**	**Channels**	**NFT**	**Containers**	**Vertical Flow**
Weaknesses					
High Initial Investment and Costs:	7	7	7	9	9
Technical Expertise Required and Maintenance Challenge:	6	6	5	8	8
Regulatory and Compliance Challenges:	5	5	5	5	5
Public Perception and Acceptance:	7	7	6	7	7
Operational Sensitivity:	6	6	5	8	8
Space and Urban Constraints:	6	7	5	8	8
Climate change	5	5	5	5	5
Complex Management	7	7	5	8	8
Health & Environmental Risks	8	8	5	8	8
Subtotal 3	57	58	48	66	66

Table 5: SWOT Analysis of Five Pilot Hydroponic Systems: Threats

Hydroponic System Type / **SWOT Titles**	**Barrels**	**Channels**	**NFT**	**Containers**	**Vertical Flow**
Threats					
Regulatory Barriers and Hurdles:	5	5	5	5	5
Environmental Risks and Contamination Challenges:	7	7	5	7	7
Market Acceptance and Competition Issues:	7	7	5	7	7
System Failures and Risks:	7	7	4	8	8
Economic Fluctuations :	6	6	6	6	6
Climate Variability	6	6	4	6	6
Social Resistance	6	6	6	6	6
Subtotal 4	50	50	41	51	51

- Phytoremediation with Hyperaccumulator Plants: Utilizing plants known for their ability to absorb and concentrate pollutants can enhance the removal of contaminants from wastewater, making the treatment process more effective.
- Application of Membrane Bioreactor and Filtration Technology: Incorporating membrane bioreactors can significantly improve effluent quality by providing advanced filtration, thereby enhancing the overall effectiveness of hydroponic wastewater treatment systems. Incorporation of advanced filtration techniques, such as membrane bioreactors (MBRs) and nanofiltration, into hydroponic systems will enhance the removal of contaminants like heavy

metals and pathogens. These methods will improve the safety and quality of treated wastewater for agricultural purposes [48].

- increase farmers' awareness and introduce them to the benefits of hydroponics and their ability to solve problem of salinity in soil by the help of media, conferences and seminars.

- **Hybrid Systems:** Combining hydroponics with other wastewater treatment methods, such as constructed wetlands or aquaponics, can improve overall system efficiency. Hybrid systems allow for multi-stage treatment, maximizing the removal of solids, nutrients, and organic matter while creating opportunities for integrated food production [49].

- **Nutrient Recovery and Circular Economy:** Future systems will focus on recovering nutrients like nitrogen and phosphorus from wastewater to create a closed-loop system. These nutrients can be directly utilized in hydroponic agriculture, reducing reliance on synthetic fertilizers and promoting sustainability [50].

- **Scalability and Modular Design:** Modular hydroponic systems are being developed to enable scalability, making them suitable for small-scale urban farms as well as large-scale agricultural operations. This modular approach will make systems adaptable to varying wastewater volumes and agricultural needs [51].

- **Regulatory Support and Incentives:** Governments and international organizations are likely to provide more incentives and establish regulatory frameworks for wastewater reuse. This will encourage widespread adoption of hydroponic wastewater systems, especially in regions facing water scarcity [52].

- **Carbon Neutral and Energy-Efficient Designs:** Future systems will emphasize low-energy designs and the use of renewable energy sources, such as solar panels, to power operations. This aligns with global goals for carbon neutrality and sustainable development [53].

- **Policy Support and Standards Development**: The success of hydroponic wastewater treatment depends on policy frameworks that incentivize adoption, including subsidies, tax benefits, and inclusion in wastewater reuse standards. International guidelines may further standardize operational practices .

CONCLUSIONS AND KEY INSIGHTS

The evaluation of hydroponic systems demonstrates varying levels of efficiency and feasibility for wastewater treatment and plant cultivation. Among the systems analyzed:

- NFT Hydroponic System: This system emerged as the most effective due to its high sustainability, nutrient recycling capabilities, operational ease, and superior contaminant removal rates. Its adaptability for both small- and large-scale farming, combined with minimal environmental risks, underscores its recommendation as a preferred choice for hydroponic farming initiatives.

- Vertical Gradual Flow System: Performing slightly below the NFT, this system is still a viable option for specific applications requiring high contaminant removal efficiencies.

- Hydroponic Barrels and Channels: These systems exhibited moderate performance but are operationally effective within niche applications. Barrels are suitable for compact, small-scale setups, while channels offer scalability but face challenges such as media clogging.

- Container and Vertical Flow Systems: These systems presented the most significant limitations in terms of strengths and opportunities, coupled with pronounced weaknesses and threats. Their adoption is recommended only for specific conditions supported by tailored technical expertise and management.

Hydroponic systems demonstrate significant potential for treating wastewater and supporting agricultural reuse, particularly in resource-limited and rural areas. Key Insights include:

- Wastewater Treatment: Hydroponic setups can achieve high removal efficiencies for pollutants like TSS, BOD, COD, and TN, ensuring effluent quality suitable for irrigation. Systems are adaptable for decentralized wastewater management in hilly or rural regions, leveraging gravity for water flow.

- Crop Performance: Crops like Faba beans and green peas thrive in nutrient-controlled hydroponic systems. Certain plants, such as musk melon, tolerate moderate salinity, offering potential in saline regions. Green peas effectively accumulate heavy metals, enhancing phytoremediation applications.

- Challenges and Recommendations: High-salinity or oxygen-demanding wastewater impacts system efficiency. Improved aeration and reduced hydraulic loads are needed for optimization. Selecting salt-tolerant crops and refining nutrient management strategies can enhance sustainability.

- Future Outlook: Hydroponic systems offer scalable solutions for wastewater reuse and agricultural productivity, aligning with sustainable water management and food security goals. With technological innovation and policy support, they can address water scarcity and environmental challenges in both rural and urban settings.

Overall, this study highlights the potential of advanced hydroponic systems, particularly NFT, as sustainable and efficient solutions for wastewater reuse and agricultural production. Continuous research, technological upgrades, and strategic implementation are essential to optimize their application and address any operational challenges.

CONFLICTS OF INTEREST

The author declared no conflicts of interest.

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