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HYDROPONICS AS A NATURE-BASED SOLUTION FOR WASTEWATER TREATMENT: NUTRIENT REMOVAL, EMERGING CONTAMINANTS, AND WATER REUSE

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ABSTRACT

Increasing water scarcity, nutrient pollution, and the demand for sustainable wastewater management have intensified interest in hydroponics as a nature-based treatment approach. This paper reviews the potential of hydroponic systems for wastewater treatment, focusing on nitrogen and phosphorus removal, emerging contaminant attenuation, and safe water reuse. A structured narrative review of peer-reviewed literature examines treatment configurations, pollutant removal mechanisms, operational limitations, and environmental and public health considerations. Findings indicate that hydroponic systems can facilitate nutrient removal through plant uptake, microbial transformations, and substrate interactions, while certain emerging contaminants may be reduced through biodegradation, sorption, and plant accumulation. However, treatment effectiveness varies with wastewater characteristics, system design, hydraulic retention time, and environmental conditions. Furthermore, contaminant accumulation in plant tissues, pathogen persistence, and incomplete degradation present significant challenges to safe reuse, particularly in food production. The review emphasizes integrating hydroponics with conventional treatment processes, implementing comprehensive water quality monitoring, and conducting long-term performance assessments. Overall, hydroponics offers a promising complementary approach to wastewater treatment and resource recovery, provided that appropriate safeguards ensure environmental sustainability and public health protection.

Keywords: Hydroponics, Nature-Based Solutions, Wastewater Treatment, Nutrient Removal, Emerging Contaminants, Water Reuse, Phytoremediation.

1 INTRODUCTION

The increasing scarcity of water, urbanization, and nutrient pollution are driving a greater demand for treatment infrastructure that recovers water and resources instead of just releasing waste. Nutrient cycling processes, especially those of nitrogen and phosphorus, fall within the planetary boundaries, which have been exceeded by human activities (Rockström et al., 2009). One of the most immediate intervention points is wastewater treatment, with the United

Nations Environment Programme (UNEP) 2023 wastewater being not only a problem to be solved but also a resource to be recovered. The same is reflected in the sustainable development agenda, as water quality, sanitation, and water reuse are tackled alongside universal access to safe water (UN-Water, 2021).

While conventional wastewater treatment works well for a number of conventional pollutants, it is not as effective for nutrients, pathogens, pharmaceuticals, personal care products, and other contaminants of emerging concern. The design principles that have been developed for municipal systems focus on staged processes, where each unit treats a certain class of pollutant (Metcalf & Eddy, 2014). Eutrophication may result from nutrient discharge, and incomplete removal of trace organic compounds can result in chronic exposure in the environment. NbS rely on nature to provide a solution, typically with minimal energy use and sometimes lower than other more engineered solutions; however, required land, climate, and performance constraints exist.

Hydroponics is traditionally known as the soilless culture of plants, in which the roots are provided with a nutrient solution. The basic plant–water interface can be used to either treat wastewater or to polish treated wastewater. Dissolved nutrients are taken up by plants, root surfaces may facilitate microbial biofilms, and substrates can act as filters and sorption surfaces. In this field, hydroponic treatment is similar to constructed wetlands and engineered ecological treatment systems, or phytoremediation. Yet, it should be used carefully, and the term "nature-based solution" should be used with care. Typical examples of hydroponic reactors are systemically engineered systems utilizing a biological process rather than a natural ecosystem.

There are two methods for the use of hydroponic wastewater treatment. First, wastewater or treated effluent can be used as an input in production, which will lead to a decrease in freshwater demand and fertilizer input. Secondly, the wastewater from hydroponic farms can be treated for the recovery of nitrogen and phosphorus for reuse or discharge. The first pathway is a food safety/exposure concern, and the second one is a nutrient loss from controlled environment agriculture. While both are applicable to circular economy principles, they need to be treated differently in terms of the goals of treatment and the methods of monitoring.

2 METHODOLOGY

Search concepts were compiled for hydroponic wastewater treatment, wastewater-fed hydroponics, nutrient removal/separate nutrients, nitrogen and phosphorus recovery, phytoremediation, constructed wetlands, pharmaceuticals, personal care products, contaminants of emerging concern, and reclaimed-water reuse, and a structured narrative review was conducted. Water research, environmental science, plant science, and agricultural engineering were the main research areas targeted for searches, which emphasized peer-reviewed research and reviews. Some of the basic literature used was included to provide background on the mechanisms in the context of system design. The mechanistic framing was informed by the principal treatment-wetland texts (Kadlec and Wallace 2009; Dotro et al. 2017), and the lessons from the constructed-wetland experience were drawn from a long-term review of experience (Vymazal 2011).

The following studies were conceptually screened for relevance to one or more of three themes: nutrient removal from wastewater or hydroponic effluent; attenuation or transformation of emerging contaminants; and safe water reuse in crop production. Experiments that tended to planted wetlands and other plant-based systems were separated from direct hydroponic experiments. The evidence from wetlands was not accepted as proof of hydroponic performance, as there are many factors that can cause a difference between hydroponic and wetland situations, such as hydraulic loading, substrate, root-zone redox conditions, and microbial communities. If information was lacking, studies were used nearby to determine possible mechanisms and research needs. No pooled removal efficiency is given since the reported wastewater composition and operating conditions vary. The percentage removal is understood in reference to the concentration of the influent, the residence time, the plant density, the hydraulic design, and the fact that the measured endpoint is a degradation or sorption or transfer to the biomass. This narrative approach is not a systematic review and may not contain all relevant publications.

3 HYDROPONIC TREATMENT CONFIGURATIONS AND REMOVAL MECHANISMS

Treatment can be done by floating rafts, nutrient film technique channels, media-based beds, or recirculating biofilters/hybrid systems. Floating systems will be in contact with a relatively large water volume and can have high plant biomass, while media-based systems will provide attachment surfaces for microbial communities and can help to improve solids filtration. Recirculation extends the contact time but can also result in the buildup of salts or compounds that may not be removed effectively. The selection of a system should thus be based on wastewater strength, the contaminants to be treated, available land, energy, crop selection, and intended wastewater reuse.

Many of the design principles are the same as with constructed wetlands. Zhang, Tan, and Gersberg (2012) discussed the principles, processes, and models of wetlands, highlighting that treatment is dependent on the interaction of the hydraulic, biological, and substrate chemistry. The behavior of nutrients in wetlands has been investigated in great detail by Vymazal (2007), who evaluated nutrient removal among various types of wetlands and determined that wetland nutrient removal was highly dependent on configuration and loading. The same applies to the removal of organics. Field experience with horizontal subsurface flow systems revealed by Vymazal and Kröpfelová (2009) indicated a close relationship between the removal of organics and oxygen present in the bed.

There are several ways nitrogen is removed. Plants take up ammonium and nitrate for protein and nucleic acid synthesis, and nitrifying microorganisms convert ammonium to nitrate in the oxygenated areas. When appropriate electron donors are present, anoxic microzones under anaerobic conditions can lead to the conversion of nitrate to N gas. At high pH, volatilization of ammonia can happen, but this is usually not desirable because it results in the release of nitrogen into the atmosphere. Even with a high plant uptake rate, continuous removal can only be maintained if harvested biomass is removed from the system. Otherwise, senescence and decomposition will release nutrients back into the water.

Table 1: Principal treatment mechanisms and operational considerations

Target	Main mechanism	Important limitation
Nitrogen	Plant assimilation, nitrification and denitrification	Uptake requires biomass harvest; redox conditions govern microbial conversion
Phosphorus	Plant uptake, microbial assimilation, precipitation and sorption	Media saturation and biomass decay can reverse removal
Suspended solids	Settling, filtration and physical retention in media	Accumulated solids require safe removal
Organic matter	Biofilm biodegradation and plant-root microbial activity	High organic loading can deplete oxygen
Trace contaminants	Biodegradation, sorption, photolysis and plant uptake	Compound-specific; transformation products may persist

A hybrid denitrification filter for hydroponic wastewater was demonstrated by Park, Craggs, and Sukias (2009), and it was shown to be capable of eliminating nitrate and phosphate levels significantly under laboratory-controlled conditions. Algae have also been studied for a polishing process of the nutrient-rich hydroponic effluents. A controlled-environment lettuce study found that algae treatment resulted in higher whole-system N and P use efficiency, demonstrating the opportunities for algae-assisted nutrient recovery and crop production. The results confirm the agri-hydroponic treatment concept, but this does not enable any hydroponic effluent to be reused without extra treatment. Main sinks of phosphorus are plant uptake, microbial assimilation, precipitation, and sorption to substrate or biofilms. In a typical treatment system, the gaseous removal pathway for phosphorus is not significant, as it is for nitrogen. It may thus enter the media or biomass and can eventually be harvested or the media changed. It is influenced by the pH, redox conditions, saturation of the substrate, and its chemistry. A design that doesn't take into account long-term media capacity can give a high initial removal rate but then slow down.

The operating variables that are critical are hydraulic retention time and loading rate. Too short a retention time will reduce the uptake of the plants and the transformation of the plants by the microbes, while too long a retention time will increase the land required, stagnation, and unwanted algal growth. Nitrification can be inhibited due to high organic loadings, which can consume oxygen. The effects of seasonal changes in temperature and light can affect the growth of plants and microbes, so it is important to consider a treatment system over a range of seasons and not within a single short-term trial.

4 REMOVAL AND FATE OF EMERGING CONTAMINANTS

Pharmaceuticals, personal care products, hormones, industrial chemicals, pesticides, and antimicrobial agents and transformation products are all examples of emerging contaminants. These properties of molecular size, ionization, hydrophobicity, volatility, biodegradability, and affinity to plant tissues or substrates affect their behavior in hydroponic treatment. Removal can be via biodegradation, phototransformation, plant uptake, sorption, and volatilization. The implication of these processes is different: biodegradation can result in the transformation of a compound, but uptake and sorption can only result in the transfer to biomass or to media.

Pharmaceuticals have been found in wastewater and reclaimed water and have been shown to be taken up by plants in hydroponic and soil culture systems. When plants were grown hydroponically and in natural environments, Madikizela, Ncube, and Chimuka (2018) observed that the roots are also significant accumulation points for pharmaceuticals. The amount of translocation to shoots is variable and depends on the physicochemical properties and species. This is important for crop safety since a compound in the root would be a different exposure question than in the edible leaf.

Examples of personal care products are parabens, triclosan and other biocides, synthetic musks, phthalates and ultraviolet filters. Fernandes, Bragança, and Homem (2024) summarized uptake and accumulation of personal care products in soil–plant and hydroponic systems, where they point out the relevance of the compound-specific behavior. A compound that is easily taken up can be removed from the water phase but can provide a crop exposure pathway. The removal of the water phase is therefore only part of the equation in quantifying treatment success when growing edible plants in the treatment unit.

Recsetar et al. (2021) tested a recirculating hydroponic bed bioreactor for the removal of contaminants of emerging concern from the tertiary treated wastewater effluent. The success of these studies was in the planted systems being used as polishing technologies; however, removal was specific to the contaminant and should not be extrapolated to all classes of contaminants. Substances can undergo rapid transformation or be persistent and/or partitioned to biomass. Transformation products might also be toxic differently than the parent compound. This is in line with previous studies on planted systems. Pharmaceutical compounds in urban wastewater have been studied by Verlicchi, Al Aukidy, and Zambello (2012), who indicated that there is a wide variation in removal after the secondary treatment and some pharmaceutical compounds are still environmentally risky. Hijosa-Valsero et al. (2011) showed that the removal of pharmaceuticals and fragrances in constructed wetlands was significantly affected by design, physico-chemical, and environmental parameters.

Another problem is the presence of antibiotic residues, since sub-inhibitory concentrations can provide for selection. Urban wastewater treatment plants have been reported as being hotspots for the release of antibiotics to the environment (Michael et al., 2013), and the same review emphasized the need to monitor residues and not presume to remove them. This worry was extended to antibiotic-resistant bacteria and resistance genes by Rizzo et al. (2013), who stated that treatment plants have the potential to be a pathway for these to be spread. If wastewater is not well characterized, a hydroponic biofilm may break down the wastewater while also allowing resistant organisms to establish themselves. Therefore, for treatment evaluation, antibiotic residues, resistance genes, and microbial safety must be evaluated, if applicable. Based on available evidence, it is not recommended to use plant-based systems as a disinfection or advanced treatment barrier alternative.

Table 2: Emerging contaminant groups and treatment concerns

Contaminant group	Potential fate in planted systems	Key safeguard
Pharmaceuticals	Biodegradation, root uptake, sorption and translocation	Analyse water and plant tissues for priority compounds
Personal care products	Sorption, transformation and plant accumulation	Select target analytes based on source and persistence
Antibiotics	Transformation or uptake; possible antimicrobial selection pressure	Monitor residues and relevant resistance indicators
Hormones and endocrine-active compounds	Biotransformation, sorption and plant uptake	Assess mixture effects and transformation products
Pathogens	Physical retention and partial die-off may occur	Use validated disinfection and multiple barriers

5 WATER REUSE, FOOD SAFETY AND ENVIRONMENTAL SAFEGUARDS

To reuse water, it should be matched to an intended end use. Use for ornamental plants, non-food crops, and industrial or environmental discharge may have varying risk levels compared to irrigation of raw-consumed leafy crops. Vymazal (2014) examined constructed wetlands for industrial wastewater treatment and found that while there is a potential for using planted systems for non-domestic streams, the contaminant profile of each stream needs to be known first to design wastewater treatment. If edible crops are involved, pathogens, chemical contaminants, salinity, sodium, and accumulation of trace elements and crop-specific accumulation are issues that must be addressed by the treatment system. Wastewater may also be rich in nutrients and may be out of balance in terms of nitrogen and phosphorus or be too high in sodium and chloride and require dilution or nutrient adjustment.

Recommendations from WHO's guidance on the use of wastewater and excreta in agriculture are based on health goals and several barriers instead of on one treatment step (WHO, 2006). Therefore, a hydroponic stage is recommended to be combined with the pre-treatment of solids removal and biological treatment upstream and with the disinfection or polishing stage downstream where applicable. This is echoed by the WHO sanitation safety planning manual, which views the entire sanitation process—from collection to final use—as a series of risks to identify, control, and verify (WHO, 2022). Crop choice, type of irrigation, routes of exposure, protective clothing for workers, and post harvest procedures are components of the safety system. Microbial risks are not necessarily controlled in hydroponic production, as the roots and channels can have biofilms.

The effects of agricultural pollution generally are another issue. The global review of water pollution from agriculture (FAO, 2017) indicates that the loss of nutrients and chemicals in agriculture can have impacts on surface and groundwater quality; thus, a hydroponic facility that discharges effluent is part of a larger water quality picture. A treatment unit that is lowering its nutrient and/or chemical concentration in its water but sending high concentrations to another location is not the solution to the problem.

Other substances such as trace contaminants and salinity can also be built up in recirculating systems. Electrical conductivity is an indirect measurement of water quality but can be used as an operational indicator and will not detect individual contaminants. Major ions and appropriate trace chemicals need to be monitored, particularly in situations where there is some variation in sources of wastewater. Nutrient supplementation must be done according to a composition measured and not according to a recipe. Pollution can be merely shifted from the old to the new solution without any treatment, thereby compromising the sustainability purpose.

6 PERFORMANCE RELIABILITY AND SCALE-UP.

Laboratory results are not necessarily indicative of reliable full-scale treatment. Typical bench-scale hydroponic reactors have a carefully controlled influent composition, consistent temperature, even lighting, and well-managed plants. The community or commercial systems have variable wastewater flows and may be interrupted, have seasonal changes in temperature, and have delays in harvesting and poor maintenance. These affect hydraulic retention, oxygen transfer, and biological activity. Constructed wetland microcosms were evaluated for removing veterinary pharmaceuticals from livestock wastewater, and while they are useful for screening, they do not necessarily capture the range of factors that may occur for operating systems. (Carvalho et al., 2013) The hydraulic loading rate, organic loading, retention time, plant density, and substrate properties as well as seasonally obtained removal percentages should therefore be reported in scale-up studies.

The second challenge is "how to distinguish between concentration reduction and mass removal?" Removal of nutrients by plants can cause an increase in the concentration of conservative contaminants measured, but evapotranspiration can lead to a decrease in water volume. On the other hand, increasing the volume of water in the system by rainwater or fresh water can decrease the concentration but not the total amount of contaminant. There are water quality measurement requirements for flow-weighted data that are required to determine accurate loads. The distinction is also important when looking at the interpretation of the removal of the pharmaceuticals. Joss et al. (2006) suggested a classification for the biological degradation of pharmaceuticals in municipal treatment; they defined the three different classes as being transformed, partially degraded, or not degraded at all. The same was illustrated by Zhang, Geißen, and Gal (2008), who found that for carbamazepine and diclofenac, the elimination from the treatment plant did not necessarily lead to the elimination from the environment. These studies confirm the rule that a decrease in the concentration in an aquarium needs to be carefully examined.

Table 3: Suggested multi-barrier treatment train for reuse

Stage	Function	Verification
Pre-treatment	Screening, grit and solids removal	TSS, turbidity and operational inspection
Primary/biological treatment	Reduce organic load and conventional pollutants	BOD, COD and nutrient profile
Hydroponic polishing	Nutrient uptake and selected contaminant attenuation	N and P mass balance; trace contaminant testing
Final barrier	Disinfection or advanced polishing where required	Pathogen indicators and reuse-standard compliance
Reuse management	Crop selection, monitoring and safe biomass handling	Crop-tissue testing and documented disposal

Operating resilience is also crucial. Harvesting is a component of treatment rather than just an agricultural operation since nutrients taken up by plant tissue are removed from the water with its removal. A late harvest can result in the release of nutrients and organic matter from senescent tissue. Treatment designs should include the frequency of harvest, biomass storage/disposal, and spent media disposal. These management activities should be considered as an integral part of operating costs and not as incidental.

Comparisons should be made on the same goals and service boundaries as what is found in traditional care. A planted system might need more space, but less electricity, and/or a compact engineered system might have more consistent pathogen reduction. A hybrid treatment combining traditional treatment to remove bulk organic matter and pathogens with a planted treatment for nutrient recovery or polishing could be the most suitable treatment. The commissioning period of the pilot project should be explicitly defined, and the variability of the influent, the plant establishment, hydraulic short-circuiting, and the maturation of microbial communities should be documented during this period.

Recommendations and Research Priorities.

Hydroponic treatment should be based on definite performance goals. The selection of crops or reactor configurations should be preceded by the establishment of target influent and effluent concentrations, intended reuse category, a seasonal range, and the required pathogen barriers by the operator and/or researchers. It is usually best to use a staged process, such as preliminary screening and settling, followed by conventional biological treatment (if required), hydroponic or wetland polishing, and final disinfection or advanced treatment (depending on the intended use). Also, the operators need to establish trigger values for maintenance, plant replacement, and media regeneration and have contingencies when the planted unit is not able to fulfill its objective. Both water quality and contaminant fate should be measured. Nutrients are the ammonium, nitrate, orthophosphate, and total phosphorus. Target lists should be based on source-water risk and analytical ability for organic contaminants. Roots and shoots and the presence of substrate and biofilm where there may be accumulation should be sampled. Pre-treatment biomass should be described prior to its reuse, composting, or disposal. Studies should not report percentage removal only and should report mass balances as well as quantify the nitrogen and phosphorus recovered in harvested biomass.

Food production systems, except when safety is established, should use a precautionary approach to separating treatment biomass from edible crop production. They can be either non-food plants as primary treatment, with a separate hydroponic crop-production stage using treated water, or a separate monitored hydroponic crop-production phase. Another involves a closed treatment system with barriers between the untreated wastewater and edible tissues. The risk, cost, and local regulatory requirements should be considered.

Future research needs involve long-term pilot testing with representative wastewater loading, multi-season operating data, pathogen and antimicrobial resistance testing, and comparisons of life cycle assessment. Further research is required with regard to the interaction between nutrient uptake and trace-contaminant accumulation and mixture effects, as well as transformation products. For implementation to be possible in low- and middle-income environments, the costs and maintenance, local markets for crops, and the availability of land and institutional capacity must be taken into account. Decentralized systems can be appropriate for peri-urban agriculture, schools, and small communities but may only be feasible where operators are able to carry out water-quality monitoring and have safe biomass management. Wastewater treatment and circular water management may be achieved with hydroponics, but not as a catch all system for generating wastewater for unrestricted reuse.

7 CONCLUSION

Wastewater treatment benefits may be added with hydroponic systems through water circulation, plant nutrient uptake, root-associated microbial activity, and substrate processes. There is some evidence that nitrogen and phosphorus loadings can be removed from certain waste streams and some evidence of reductions in some emerging contaminants. Performance, however, is highly dependent on system design and wastewater properties, and the removal of a contaminant from water may be a transfer instead of a destruction.

Reuse should only be done safely if pathogen barriers are validated, chemical monitoring is performed, and a crop-specific risk assessment and responsible handling of harvested biomass and spent media are done. The right treatment can be used to promote circular water management with hydroponics, with proper precautions and over-time evaluation. So far, however, no evidence exists to support the claims of universal contaminant removal or of unrestricted reuse of food crops.

STATEMENTS ON COMPLIANCE WITH ETHICAL STANDARDS

Disclosure of conflict of interest

The authors declare no conflicts of interest regarding this manuscript.

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