

Phytoremediation of Hospital Wastewater: Removal Mechanisms, Microbial Biofilm Dynamics, and Implementation in Resource-Limited Settings

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Abstract

Hospital wastewater contains a variety of contaminants, including organic waste, pharmaceutical residues, and harmful microorganisms. They are also grounds for the evolution of antibiotic resistant bacteria. While conventional wastewater treatment can remove many pollutants, some contaminants may remain and enter surrounding water systems, creating risks for both human health and the environment. Subsurface-flow constructed wetlands offer a potential low-energy solution by using natural processes, including filtration, adsorption, and microbial activity, to treat wastewater closer to its source. However, these systems also have limitations, as their ability to remove complex contaminants such as pharmaceutical residues and antibiotic resistance bacteria depends on factors including wetland design, climate, and maintenance. In this article, we examine the role of constructed wetlands in hospital wastewater treatment while analyzing their effectiveness, challenges, and potential as a complementary approach to conventional treatment systems.

Introduction

Hospitals around the world generate large amounts of wastewater that pose potent threats to human health and the environment. On average, hospitals use 40-60L/day for every patient with developed countries producing almost three times more wastewater than developing countries (Kumari et al., 2020). Compared to domestic wastewater, HWW stores high amounts of antibiotics and disinfectants that originate from patient excreta and improper drug disposal. These compounds create selective pressure that facilitates the growth of microorganisms, including antibiotic-resistant bacteria, which may persist in drinking water sources and directly threaten human health (Majumder et al., 2021). In addition, when improperly treated or discharged, these contaminants can enter watersheds and pollute both surface and groundwater (Biswal, 2013).

Current Treatments

Most municipal treatment plants are primarily designed to filter organic matter, suspended solids and nutrients. They do not efficiently remove biomedical waste (Majumder et al., 2019). Furthermore, there is evidence of developing countries like Algeria, Congo, Nepal, etc., releasing their sewage into water bodies without any treatment (Al Aukidy et al., 2017). Even in countries

where treatment is available, conventional technologies such as advanced oxidation processes, activated sludge systems, membrane bioreactors, and constructed wetlands have limitations. Yet, the antibiotic resistance microorganisms and antibiotic residues were found to be persistent even after treatment (Petrovich et al., 2020).

These limitations highlight the need for sustainable and more effective treatment strategies capable of targeting both antibiotic residues and resistant microorganisms. One promising approach is phytoremediation.

Phytoremediation

Phytoremediation is the use of plants and their associated soil microbes to remove, degrade, stabilize, or reduce the toxicity of environmental contaminants. It is considered a cost-effective and environmentally friendly alternative to traditional engineering-based cleanup methods, which can damage soil (Greipsson, 2011). For HWW phytoremediation is particularly attractive because it can simultaneously target pharmaceutical compounds, including antibiotics, while improving water quality through multiple biological processes. Depending on the contaminant and plant species involved, phytoremediation operates through several distinct mechanisms.

a) Phytoextraction, Phytostabilization and Rhizofiltration:-

- i) All three methods are complementary phytoremediation mechanisms that remove or sequester contaminants, particularly heavy metals through plant-root action. Phytoextraction is the process by which plants absorb contaminants, particularly heavy metals, through their roots and transport them to aboveground tissues such as stems and leaves. Inside the plant, the metals bind to molecules such as phytochelatins or other ligands. Once sufficient contaminants have accumulated, the plants are harvested and removed, thereby extracting pollutants from the contaminated site.

b) Phytodegradation and Rhizodegradation

- i) Phytodegradation involves the uptake of organic contaminants by plants, followed by their breakdown into less toxic compounds through plant metabolic processes and enzymes. Together, these mechanisms are particularly effective for organic pollutants such as pesticides, petroleum hydrocarbons, pharmaceuticals including antibiotics, and chlorinated compounds, converting them into simpler, less harmful substances (Kafle et al., 2022).

Plant Selection and Combinations

Once a hospital has decided to implement a constructed wetland, appropriate plant species must be selected for the system. This section examines the role of plants in constructed wetlands and the species commonly used in gravel-bed systems. It also explains why popular floating plants

are unsuitable for this design and whether using multiple plant species provides additional benefits.

What the Plants Actually Do

The term *phytoremediation* suggests that plants are the primary drivers of pollutant removal; however, it is important to understand the extent to which plants directly contribute to the treatment process.

Most of the chemical breakdown happens through bacteria living in the gravel and on the root surfaces, not through plants absorbing pollutants into their tissue. Studies that track antibiotics through wetland systems find that microbial degradation, meaning the breakdown of drug molecules by bacteria, accounts for the majority of contaminant removal. Uptake into plant tissue is a smaller share (Chen et al., 2019; Liu et al., 2019).

Plants nevertheless play an important role, because they build the conditions those bacteria need. Roots release oxygen into gravel that would otherwise hold almost none, and the bacteria that break down organic waste and convert ammonia cannot perform these processes without it. Bacteria live in biofilms, which require solid surfaces for attachment, and every root provides additional habitat for microbial communities. Roots also release sugars and other carbon compounds into the surrounding gravel, which serve as a carbon source for bacteria (Karathanasis et al., 2003; Parashar et al., 2022).

Which Species Go in the Gravel Bed

Two plants appear in most subsurface systems built for hospital wastewater: cattail (*Typha latifolia*) and reeds of the genus *Phragmites*. Both come back year after year without replanting, both survive heavy pollution loads, and both can usually be dug up from local ponds and riverbanks instead of bought. A team in India, the Ujjain team collected their own from nearby water bodies (Parashar et al., 2022).

The Ujjain study directly compared the performance of the two plant species with an unplanted gravel control. Six identical cells were built. Two were planted with cattail, two with the South Asian reed *Phragmites karka*, and two were left unplanted as controls. Across six different pollutants, the three cell types performed differently by a margin large enough that chance was an unlikely explanation.

Neither plant won across the board. Cattail removed the most fecal coliforms, at 96.8%. Fecal coliforms are gut bacteria used worldwide as the standard indicator that water has been contaminated by human waste. The reed cells did better on turbidity, meaning cloudiness, at 68.3%, on suspended solids, meaning the fine particles floating in the water, at 63%, on phosphorus at 58.7%, on nitrate-nitrogen at 33%, and on total coliforms at 95.6% (Parashar et al., 2022).

The results for resistant bacteria did not follow that pattern. The team collected *Escherichia coli*, a gut bacterium, from the incoming wastewater and tested it against two widely used antibiotics, ciprofloxacin and sulfamethoxazole. Before treatment, 55.6% of the *E. coli* survived ciprofloxacin and 41.1% survived sulfamethoxazole. After the water passed through the cattail cells, those shares fell to 37% and 31.67%. The unplanted gravel controls brought them to 50% and 39.44%. The reed cells did not reduce them, and the share surviving ciprofloxacin came out higher than it went in. The authors suggest the reed bed may have provided growing conditions that bacteria tolerated well (Parashar et al., 2022). One site studied over two years cannot rank the species. It can show that a wetland which cleans a water sample by the usual measures is not guaranteed to remove the resistant bacteria that motivated building it.

For a system built in Canada, the law may decide the choice before performance does. *Phragmites karka* grows in tropical and subtropical regions (Nayak et al., 2020) and would not survive a Canadian winter. The reed that does grow in this climate, *Phragmites australis* subsp. *australis*, cannot be planted here. Ontario lists it as a restricted species under the Invasive Species Act, 2015, making it illegal to grow, buy, sell or transport, because it forms dense stands that crowd out native wetland plants (Ontario Invasive Plant Council, n.d.). A hospital here copying the Ujjain design would have to substitute cattail or the native subspecies, *Phragmites australis* subsp. *americanus*, which does not spread the same way.

Floating Plants and Where They Fit

Duckweed and water hyacinth appear in almost every discussion of cleaning water with plants, so it is worth explaining why neither belongs in the system described here.

Both float on the surface, and a subsurface bed deliberately keeps the water below the gravel, where there is no open surface for a floating plant to sit on. They belong to a different design, either a free surface wetland, which looks like a shallow pond, or a polishing pond placed after the gravel bed to catch what the bed missed.

Duckweed (*Lemna* species) grows fast, pulls nitrogen and phosphorus out of the water, and can be skimmed off and carted away, which physically removes those nutrients from the site. It fails in a specific and documented way. At a wetland serving the town of Forano in central Italy, the middle of three treatment pools performed worse than the two around it, and the duckweed was the reason. The mat had thickened to 18 to 30 mm, enough to block sunlight and cut off the water's contact with the air. The water below went dark, cool and nearly oxygen-free, which stopped the oxygen-dependent bacteria from working. The dead fronds at the bottom of the mat then released their stored nutrients back into the water, so nitrate and phosphate levels were higher leaving the pool than entering it (Ceschin et al., 2019). Duckweed only works if someone harvests it on a schedule.

Water hyacinth (*Eichhornia crassipes*) absorbs a wide range of organic contaminants and produces large amounts of plant matter quickly. It is also among the most damaging aquatic

weeds in the world, blocking waterways and disrupting freshwater supply in tropical regions on several continents (Kriticos & Brunel, 2016). It changes habitat in ways that matter directly for human health. In Lake Victoria, water hyacinth mats were linked to larger populations of *Biomphalaria* snails, which carry the parasite that causes schistosomiasis, a disease people contract through contact with contaminated fresh water (Plummer, 2005). Installing it beside a hospital in a tropical low-resource setting works against the reason for building the wetland.

One Species or Several

The last decision is whether to plant a single species or mix them, and the evidence here is genuinely unsettled.

The Ujjain split is an argument for mixing. Cattail handled organic waste and fecal bacteria better, reed handled solids and nutrients better, so a system running both would cover more of the pollutant range than either alone. Combinations are used in practice. Cattail grown together with water hyacinth or water lettuce gave steady ammonia removal of 35 to 40% in open surface wetlands in India (Datta et al., 2016).

The wider literature does not resolve it. Most constructed wetlands in operation are planted with one species, and studies comparing single-species beds against mixed beds have reached contradictory conclusions (Luo et al., 2023). Whether mixing helps seems to depend on which species are combined, what kind of wetland it is, and which pollutant is being measured. Luo and colleagues found the clearer benefit came from combining plants with different growth forms, meaning different root shapes and rooting depths, rather than simply from adding more species.

A separate argument for mixing does not depend on removal rates. A bed holding more than one species is less likely to fail completely if one species dies back over a cold winter or cannot tolerate a change in the wastewater coming from the hospital. For a facility with no dedicated operator, that margin of safety may be worth more than a few percentage points of removal.

Plant choice is also not the largest variable in play. The Ujjain wetland removed 64.9% of chemical oxygen demand while receiving water at a hydraulic loading rate of 1.016 metres per day, meaning the depth of wastewater fed onto each square metre of bed daily. A *P. karka* system in Ethiopia removed 94% at 0.025 metres per day (Angassa et al., 2019; Parashar et al., 2022). The plants were comparable. The rate at which water was pushed through them was not. How the bed is sized and how long the water stays inside it, covered next, sets the limits that plant selection has to work within.

Protecting Downstream Water Sources

When hospital wastewater enters public sewer systems without being treated first, some drug residues, resistant bacteria, and resistance genes may pass through the treatment process and enter nearby rivers, lakes, and shallow groundwater (Mackul'ak et al., 2021).

Once these pollutants enter natural water systems, they can create both environmental and public health risks. Low concentrations of antibiotics in rivers may expose bacteria to the drugs without killing all of them. This creates selective pressure, meaning resistant bacteria are more likely to survive and reproduce. Resistance genes can also move between bacteria through horizontal gene transfer, when one bacterium passes genetic material to another, allowing resistance to spread through bacterial populations (Kotwani et al., 2021). The risk is especially serious when hospital pollutants reach shallow groundwater. Nearby communities may depend on these water sources for drinking, cooking, and washing, creating a direct pathway for exposure to resistant bacteria (Kusi et al., 2022).

Treating wastewater directly at the hospital creates an extra barrier before these pollutants enter public sewer systems and natural water sources (Verlicchi et al., 2012). By stopping these contaminants closer to their source, hospitals can reduce the spread of antibiotic resistance and help protect nearby rivers, groundwater, and community drinking wells.

How Underground Constructed Wetlands Treat Hospital Wastewater

Some wastewater treatment systems move water underground through layers of gravel, sand, or soil and around plant roots. These systems are called subsurface flow constructed wetlands. As wastewater moves through the basin, suspended solids and other contaminants become trapped in the small spaces between gravel particles. The gravel also provides a large surface area where microorganisms can grow and interact with the wastewater. Together with the plant roots discussed earlier, these microorganisms help break down organic waste and trace pharmaceutical residues (US FRTR, n.d.). Because treatment occurs below the gravel surface, the system combines physical filtration with the biological treatment processes already described in the phytoremediation and plant-selection sections.

Real-World Case Study

While the previously discussed Ujjain case study highlights plant-specific removal efficiency, the following installation at Dhulikhel Hospital demonstrates how constructed wetlands function under continuous, real-world demand.

Dhulikhel Hospital, Nepal

In Nepal, Dhulikhel Hospital established a decentralized constructed wetland in 1997 alongside researchers and the Environment and Public Health Organization (ENPHO) because it was understood to be a low-cost wastewater treatment option (Shrestha & Maharjan, 2009). Being decentralized meant the hospital could treat wastewater on-site rather than relying on a large municipal sewer network. *Phragmites karka* was the primary vegetation used in this experiment.

The wetland was originally designed to handle 10 cubic metres of wastewater per day, but as the hospital grew, it successfully treated more than four times that amount, showing that the system

could scale well beyond its original design. Based on six years of experience with constructed wetlands in Nepal, ENPHO reported removal rates above 95% for major pollutants like suspended solids, organic matter, and ammonia-nitrogen, though this alone doesn't confirm the treated water met every safety standard. The system was also cheaper to build, run, and maintain than larger treatment technologies. Its performance satisfied the hospital enough to expand its treatment capacity (Shrestha & Maharjan, 2009).

The Dhulikhel Hospital experiment shows that this approach can work beyond a controlled experiment and be practical in real-world settings.

Real-World Engineering Constraints

Although constructed wetlands have been shown to work in practice, they still have limitations and require careful site-specific engineering.

Land Availability

- Subsurface constructed wetlands usually require more land than mechanical treatment systems.
- May limit their use at hospitals in crowded areas where little open space is available (US EPA, 1993).
- Because the wastewater remains below the gravel, the system can be placed closer to hospital buildings with less risk of:
 - Exposed wastewater
 - Odours
 - Mosquito breeding
- More practical when a hospital has sufficient nearby land to safely construct the treatment bed.

Local Climate

During winter:

- Plant growth slows.
- Microorganisms that break down pollutants become less active.

Without design adjustments, cold weather can reduce how effectively wetland systems treat wastewater.

Engineers adapt the system by:

- Building deeper treatment beds.
- Keeping wastewater below the frost layer.
- Using mulch, dry leaves, and even snow to help insulate the surface.
- Lengthening the time wastewater spends in the system.

This gives microorganisms more time to break down contaminants when treatment processes slow during colder weather (US FRTR, n.d.).

Controlled Flow

- The gravel, bacteria, and plants cannot treat wastewater effectively if it moves through the system too quickly.
 - The water must remain inside the system long enough for removal processes to occur, a period called the hydraulic retention time (United States Environmental Protection Agency, 1993).
- A longer retention time gives solid particles time to settle or become trapped and allows microorganisms more time to break down pollutants.
 - Engineers must therefore control how quickly wastewater enters and moves through the treatment bed based on the pollutants being removed and the treatment conditions required (US FRTR, n.d.).

Cost of Implementation

One of the biggest barriers is the initial construction cost.

Building the system requires:

- Preparing and excavating the land.
- Installing a waterproof liner and pipes.
- Filling the basin with large amounts of gravel or sand (Government of Canada, 2017).

Once built, the wetland can be inexpensive to operate.

Gravity moves the wastewater through the system, while plants and microorganisms help remove pollutants naturally.

Reduces the need for:

- Continuous pumping
- Mechanical aeration
- Added chemicals
- Large amounts of electricity used for mechanical filtration (Government of Canada, 2017).

Still requires basic maintenance:

- Managing plant growth
- Checking for sediment buildup
- Inspecting pipes and valves

These tasks are generally less demanding than maintaining complex mechanical equipment.

Overall, most costs occur during construction. Low electricity and maintenance requirements help offset these expenses over time.

Conclusion

Hospitals produce wastewater containing organic waste, pharmaceutical residues, harmful microorganisms, and antibiotic-resistant bacteria. When this wastewater is released without proper treatment, these contaminants can enter rivers, groundwater, and nearby drinking-water sources. Subsurface constructed wetlands offer a possible on-site solution by moving wastewater

through gravel, plant roots, and microbial biofilms that work together to remove different forms of pollution.

The Ujjain and Dhulikhel case studies show both the potential and the limits of this approach. The Ujjain wetland removed large amounts of organic waste, suspended solids, nutrients, and fecal bacteria, although its effect on antibiotic-resistant bacteria depended on the plant species used. The Dhulikhel system showed that constructed wetlands can continue operating as a hospital grows and can provide decentralized treatment where access to larger municipal systems may be limited. However, these results do not mean that constructed wetlands remove every pharmaceutical residue, resistant bacterium, or resistance gene.

Constructed wetlands also come with important engineering challenges. They require enough available land, treatment may slow during colder weather, and the gravel can become clogged if larger solids are not removed first. Their performance also depends on how quickly wastewater enters the system, how long it remains inside, and whether the plants and treatment bed are properly maintained. For these reasons, constructed wetlands must be designed for the specific hospital and local environment rather than copied directly from another location.

Constructed wetlands cannot remove every hospital wastewater contaminant, and additional treatment or disinfection may still be required. However, they can reduce the amount of pollution entering municipal sewers and natural water sources before more advanced treatment is needed. Their greatest value is therefore as a low-energy, on-site treatment method that can provide an additional layer of protection without depending on expensive machinery, large amounts of electricity, or continuous chemical inputs.

This connects directly to the mission of The Student Water Project. Low-cost water technologies are valuable in communities with limited treatment infrastructure, while also helping address gaps in existing systems by treating pollution closer to its source and reducing the burden on municipal treatment plants.

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