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Research Article

A SMART APPROACH OF QUALITY BY DESIGN TOWARDS PHYTOREMEDIATION

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Abstract

This review article addresses the inherent variability and lack of process control in phytoremediation, a promising green technology for water treatment. We propose a novel framework by applying the principles of Quality by Design (QbD), a systematic approach from the pharmaceutical industry, to a water hyacinth-based system. This framework defines the desired water quality as Critical Quality Attributes (CQAs) and identifies Critical Process Parameters (CPPs), such as plant density, treatment duration and water pH, that must be actively controlled. By leveraging Process Analytical Technology (PAT) for real-time monitoring, this model transforms phytoremediation into a reliable, scalable, and reproducible engineering solution. The QbD approach ensures consistent performance, mitigates risks and provides a robust, data-driven strategy for achieving regulatory compliance.

Keywords: Phytoremediation, Quality by Design (QbD), Wastewater treatment, Water hyacinth.

Introduction

Water is a crucial natural resource, sustains life and environment. Two primary categories of natural water resources are surface water and groundwater, play indispensable roles in meeting various human needs.

Prevalence of water pollution

According to an analysis based on 625 studies collected from 63 nations, the world's water quality has deteriorated due to the growth of urban places [1]. The World Health Organization (WHO) states that around 2 billion people worldwide consume water that is contaminated. Globally 44% of household wastewater is not properly treated [2]. Globally, in 2022, about 113 billion m^3 of household wastewater went untreated translating to nearly 78.5 million m^3 per minute discharged into the environment [3]. In India's urban areas, of roughly 72,368 MLD of sewage generated, only 28% is treated, meaning 72% remains untreated, which equals approximately 36.2 million L per minute entering water bodies untreated [4].

Globally, nearly 2 million metric tons of wastewater are dumped into water bodies, particularly affecting poorer nations where surface water bodies receive a significant proportion of untreated industrial effluents and raw sewage [5]. The presence of harmful chemicals in water has a detrimental impact on the water environment by obstructing light penetration, which stops aquatic plants from photosynthesis [6]. Heavy metals can be the primary reasons of conditions such as skin disorders, dehydration, cancer, respiratory issues, asthma, problems with cardiovascular and excretory systems, nervous and immune system disorder and stunted growth in humans [7].Traditional waste water treatment methods, such as distillation systems or using physicochemical techniques like ion exchange, adsorption, reverse osmosis and UV treatment have been utilized. However, these techniques often generate sludge and are time-consuming, expensive and inefficient [8]. In recent years, an environmentally friendly technology phytoremediation, has gained more prominence as an alternative for wastewater treatment.

Types of contaminants

- **Organic pollutant**

  Industries heavily depend on various dyes and chemicals for the synthesis of diverse products, notably cosmetics, medicines and clothing. Despite their industrial benefits, concerns are mounting over their environmental repercussions, specifically focusing on waterborne organic pollutants characterized by extended half-lives [9].

  - ✓ **Pesticide:** Pesticides are synthetic and organic, such as Dichlorodiphenyltrichloroethane (DDT), endrin, aldrin and chlorinated hydrocarbons like chlordane, have a tendency to build up in food chains.
  - ✓ **Petroleum hydrocarbon:** Oil industries, particularly during production, refining, transportation and storage processes, play a substantial role in water pollution through the discharge of oily wastewater [10].

- **Inorganic pollutant**

  Inorganic pollutants encompass industrial waste, nutrients, heavy metal, and sediments [11]. Although many of these pollutants exist naturally, human activities like agriculture, mining and industrial processes have escalated their amounts in the environment [12].

  - ✓ **Heavy metals:** like Co, As, Hg, Pb, Cu, Cd, Zn, Ni and Cr enter water bodies and persist in various oxidation states for extended periods [13].
  - ✓ **Phosphorous and nitrogen:** The primary sources of Nitrogen and Phosphorus pollution in water bodies are the result of sewage effluents originating from detergents and human waste and excess agricultural nutrients.

Phytoremediation is a plant-based approach, which involves the use of plants to extract and remove elemental pollutants or lower their bioavailability in soil [14]. Phytoremediation technology is an emerging green approach used to detect, degrade and remove various types of pollutants from the environment. Plants have the abilities to absorb ionic compounds in the soil even at low concentrations through their root system. The mechanism involves is absorption of pollutants through roots, accumulation in body tissues, decompose and transforming pollutants to a less harmful forms. The versatility of phytoremediation extends its applicability to various purposes, including wastewater treatment, purification of surface and groundwater, recovery of soil affected by natural disasters and the elimination of excessive nutrients from water basins [15]. Phytoremediation comes out as a viable, economical and efficient cleanup technique for treating groundwater, wastewater and contaminated soil. Plant species, namely *Eichhornia sp., Salvinia sp., duckweed, Azollasp., Typha sp., Scirpus sp., Limnocharisflava, Potamogeton sp., Myriophyllum sp., Spartina sp., Cyperus sp., and Phragmites sp.,* have demonstrated significant potential in eliminating heavy metals from wastewater [16].

Types of phytoremediation

- ✓ **Phytoextraction** is a technique involving the cultivation of plants in polluted areas with the ability to accumulate heavy metals, facilitates the harvesting of metal enriched biomass upon maturity [17].
- ✓ **Phytostabilization** relies on plants' exceptional ability to absorb and store pollutants, leading to their immobilization or solidification [18].
- ✓ **Phytodegradation**, in which enzymatic activity of plants and their associated microbes convert organic contaminants into simpler molecules [19].
- ✓ **Phytovolatilization**, in which pollutants are converted into hazardous compounds by green plants, utilizing the plant's stomata to release volatile substances into the surrounding environment [20].
- ✓ **Rhizofiltration,** in which plant roots absorb, concentrate and precipitate (such as heavy metals or excess nutrients) from polluted water [21].

Advantages:

Phytoremediation is a cost-effective and environmentally friendly approach to cleaning up contaminated sites. It offers several advantages over traditional engineering methods.

- **Cost-Effectiveness**: This technology is significantly cheaper than conventional methods like excavation and soil incineration, which can cost up to ten times more. After the initial planting, the operational and maintenance costs are low, as the process is solar-powered and requires minimal labor and specialized equipment [22-24].

- **Environmental Sustainability:** Phytoremediation is considered a "green" technology that uses naturally occurring processes and living plants to treat contamination [24, 25].

- **Aesthetic and Social Benefits:** Unlike industrial remediation techniques that can be disruptive and visually unappealing, phytoremediation sites are often aesthetically pleasing and can even enhance the landscape with plant growth. This can lead to greater public acceptance and support for the project [24, 26].

- **In-situ Treatment:** The process can be conducted on-site without the need to excavate, transport and dispose of contaminated material. This minimizes the risk of spreading contaminants during transport and reduces the overall carbon footprint of the cleanup effort [23,27].

- **Permanent Contaminant Removal:** Phytoremediation can permanently remove contaminants from the environment by accumulating them in plant tissues for safe disposal (phytoextraction) or by breaking them down into less harmful substances (phytodegradation) [23, 28]. For valuable metals, a process called "phytomining" may even allow for their recovery [29].

- **Disadvantages:**
  - **Slow Process:** Phytoremediation is a time-intensive process that can take many years or even decades, to achieve target cleanup levels, particularly in heavily contaminated areas. This can be a major drawback for sites that require rapid remediation [30,31].
  - **Limited to Rooting Depth:** The effectiveness of the technology is restricted to the depth of the plant roots, which is typically a few meters for soil and less than 10 meters for groundwater. Contaminants located deeper in the subsurface are not accessible to this method [31,32].
  - **Contaminant Specificity and Bioavailability:** The efficiency of phytoremediation is highly dependent on the plant species' tolerance for specific pollutants and the bioavailability of the contaminants in the soil or water. Not all plants can effectively remove all types of pollutants and high levels of toxicity may even be harmful to the plants themselves [31-35].
  - **Risk of Food Chain Contamination:** If not managed properly, harvested plant biomass containing accumulated contaminants can pose a risk of entering the food chain if consumed by wildlife [31, 36]. There is also a risk of secondary pollution if the contaminated plant material is not disposed of correctly, as pollutants can re-enter the environment through decaying plant matter [37].
  - **Dependence on Environmental Conditions:** The process is susceptible to fluctuations in environmental conditions, such as temperature, seasonal changes and rainfall, which can affect plant growth and consequently, remediation efficiency. This makes the results less predictable compared to engineered, self-contained systems [31].

Applying of QbD in phytoremediation using *water hyacinth*

The limitations of small-scale, ad-hoc studies highlight the need for a rigorous, science-based framework to develop wastewater treatment processes that are both scalable and reliable. The Quality by Design (QbD) concept, a systematic approach focused on process understanding and control, offers the ideal blueprint for this purpose [38]. Originally developed for the pharmaceutical industry, QbD is well-suited for biological systems like phytoremediation due to its emphasis on managing variability in raw materials and complex multi-step processes [39].

Criteria for selection of *water hyacinth*

- **Rapid growth rate:** Water hyacinth grows quickly and produces high biomass, which enhances its pollutant uptake capacity.
- **Heavy metal accumulation ability:** Capable of absorbing heavy metals like lead (Pb), cadmium (Cd), chromium (Cr) and mercury (Hg) efficiently.
- **Floating aquatic plant:** Easy to deploy and maintain in surface water bodies such as ponds, lakes and wastewater systems.

- **Large root surface area:** Its extensive fibrous roots provide a large surface area for absorbing pollutants, including nutrients and toxins.
- **Absorption of nutrients:** Effectively removes nutrients such as nitrates, phosphates and ammonia helps to prevent eutrophication.
- **Adaptability:** Tolerates a wide range of pH levels, temperatures and pollutant concentrations making it suitable for diverse environments.
- **Low cost & easy maintenance:** Does not require fertilizers or pesticides and thrives in nutrient-rich wastewater making it cost-effective.
- **Biomass can be harvested:** The polluted plant biomass can be easily removed and processed, preventing the release of accumulated contaminants back into the environment.

- **Quality Target Product Profile (QTPP)**

  For a water hyacinth phytoremediation system, the "product" is the treated water. The QTPP would therefore define the desired final state of the water to ensure its quality, safety and suitability for its intended use, whether for discharge or reuse [40].

- **Critical Quality Attributes (CQAs)**

  These are the measurable characteristics of the treated water that must fall within a specific limit or range to ensure the desired quality [41]. For water hyacinth phytoremediation, important CQAs include:

  - ✓ Final concentration of target heavy metals (e.g., Pb, Cu, Cr). Some studies report removal efficiencies over 70% for heavy metals like copper, lead and cadmium, with lead removal reaching 92.4%.
  - ✓ Final concentrations of nutrients (e.g., nitrates, phosphates). Some studies show removal efficiencies of nutrients like nitrates and phosphates can be less than 50%.
  - ✓ Final physicochemical parameters: pH, BOD, and COD.

- **Critical Process Parameters (CPPs)**

  These are the variables that must be controlled to ensure the CQAs are met [41]. Based on the available evidence, the primary CPPs for this process are:

  - **Plant Density:** Higher plant density (e.g., 2 kg of water hyacinth per drum) results in more rapid and effective purification compared to a moderate density (e.g., 1 kg). This suggests that plant biomass must be carefully managed as a important input variable [42].
  - **Treatment Duration:** The time required to achieve the desired level of purification varies by pollutant. While rapid absorption may occur within the first three weeks, optimal heavy metal removal efficiencies of over 90% have been observed after 30 days [42].
  - **pH of the Water:** Water hyacinth can tolerate a wide pH range (4 to 10). The sorption of heavy metals is highest at a pH of 6.0 and lowest at a pH of 2.0.Thus, pH must be actively controlled to maximize process efficacy.
  - **Temperature:** The optimal temperature for the plant’s growth, which directly influences its metabolic and absorption rates is 28–30°C. This is an important environmental consideration for system design and location.

- **Risk Assessment**

  A risk assessment would examine how variations in environmental factors, such as water temperature, nutrient composition, or pollutant concentration could negatively impact the plant's growth and its ability to absorb contaminants.

- **Process Design Strategy**

These parameters should be studied through:

- Design of Experiments (DoE) to establish robust operational ranges and account for seasonal variability.
- Process Analytical Technology (PAT) allows for real-time, in-line measurement of both CPPs and CQAs [43].

This ensures that the process operates consistently within the defined "design space," minimizing variability and reducing the likelihood of batch failure [41].

Recommended PAT tools include:

- **Raman and UV Spectroscopy** [44].
- **In-line Sensors:** Continuous monitoring of important CPPs such as pH, temperature and dissolved oxygen (DO) [43].

The application of PAT transforms phytoremediation from a static, unpredictable biological process into a dynamic, "monitor-and-adjust" system.

Rationale for adopting QbD model

- **Enhanced process understanding:** QbD approach systematically identifies the relationship between the process variables (CPPs) and the desired outcomes (CQAs). By using tools like Design of Experiments (DoE), it is possible to understand how factors like pH, temperature, and nutrient concentration affect contaminant removal efficiency and plant growth, leading to a deeper scientific understanding of the process [45,46].

- **Improved process control and reliability:** QbD emphasizes real-time monitoring and control to ensure a process remains within a defined "design space". Using Process Analytical Technology (PAT) tools to continuously monitor key parameters such as pH and dissolved oxygen allows for immediate intervention, ensuring consistent performance and preventing process deviations that could reduce efficiency or cause harm [45,46].

- **Increased predictability and reproducibility:** Traditional phytoremediation can be highly variable due to environmental factors. QbD provides a structured approach to control this variability, making the process more predictable and the results reproducible [45, 47].

- **Supports regulatory compliance and standardization:** By adopting QbD approach, the phytoremediation technology can be elevated from a variable, site-specific solution to a standardized process with clear metrics, data-driven performance targets, and a robust control strategy. This is crucial for gaining regulatory acceptance for large-scale environmental projects [48].

- **Mitigates ecological and process risks:** A core component of QbD is risk assessment, which allows for the proactive identification and mitigation of potential failures before they occur [45, 47]. This is vital for phytoremediation, where risks include secondary pollution from decomposing biomass, invasive plant growth, or inefficient contaminant removal, all of which can be addressed through a formal risk-based control strategy [49,50].

Conclusion

Phytoremediation using water hyacinth offers a sustainable and eco-friendly solution for water purification. By integrating Quality by Design (QbD) frameworks into the remediation process, this review article proposes a smart and scalable approach that enables real-time monitoring and improved control. The biosorption mechanism supported by QbD tools such as PAT and DoE, enhances predictability and also ensures regulatory compliance and process reproducibility. This combined model bridges the gap between environmental science and pharmaceutical-quality process management making it an ideal candidate for future wastewater treatment technologies.

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