



DESIGN AND ANALYSIS OF A MODULAR WATER HYACINTH-BASED PHYTOREACTOR FOR EFFICIENT POLLUTANT REMOVAL IN DOMESTIC WASTEWATER

Author Details: Mr Tapash Kumar Ghosh,
Lecturer(SS) in Mechanical Engineering
Goalpara Polytechnic, Assam, India

ABSTRACT

Household wastewater is hurting the environment more and more, therefore we need to discover ways to clean it that are cheap and last a long time. Using aquatic macrophytes like water hyacinth (*Eichhornia crassipes*) for phytoremediation is an excellent idea since they grow quickly, make a lot of biomass, and are better at soaking up contaminants. This study delineates the design and evaluation of a straightforward modular phytoreactor utilizing water hyacinth for the effective elimination of organic and inorganic pollutants from home wastewater. This research expands upon previous investigations focused on the extraction of phytochemicals such as shikimic acid, phenolics, and antioxidant compounds from water hyacinth, alongside lignin and cellulose from lignocellulosic materials. It stresses the benefits of cleaning up pollutants and using biomass in a way that adds value.

We looked at the physicochemical and microbiological properties of wastewater samples and set up phytoreactor modules with set retention times. Water hyacinth was acclimatized and utilized in reactor units, with the efficacy of pollutant removal assessed by measuring the reduction in COD, BOD, nutrients (nitrogen, phosphorus), heavy metals, and microbiological loads. We used analytical tools like FTIR, HPLC, and spectrophotometry to help us keep an eye on things. The results showed that the water got better as time went on. A lot of minerals and organic substances were gone. Studies on the biomass of water hyacinth demonstrated the feasibility of recovering lignin, cellulose, and secondary metabolites, thereby endorsing the concept of a cyclical biorefinery model.

The results show that modular phytoreactors provide a scalable, cost-effective, and long-lasting way to treat wastewater without the need for a central facility. They also aid with resource recovery and are excellent for the environment and the economy, which is what sustainable development is all about.

Keywords: Water hyacinth (*Eichhornia crassipes*); Phytoremediation; Domestic wastewater treatment; Modular photoreactor; Resource recovery

INTRODUCTION

There are a lot of germs, heavy metals, nutrients, suspended particles, and organic matter in home wastewater. This is bad for the environment. People commonly clean up sewage with activated sludge, trickling filters, and systems based on membranes. But they use a lot of power, need experienced workers to run them, and cost a lot to buy and keep running. There is a rising need for inexpensive, eco-friendly, and mechanically flexible ways to deal with wastewater in a decentralized way, especially in places that are not fully urban or rural. (Abuzer and Huseyin, 2011)

Using aquatic plants for phytoremediation is a natural technique to clean up the environment that can work well with ideas for engineering design. Water hyacinth (*Eichhornia crassipes*) is a type of macrophyte that has gotten a lot of attention because it grows quickly, has a high surface-to-volume ratio, and may take up pollutants through its roots and tissues. Water hyacinth is a weed that grows swiftly, yet it may be utilized to clean up wastewater and turn biomass into something valuable if it is handled properly in engineered systems. By merging biological remediation with modular system design, mechanical engineers can now make systems that work better, can grow, and last longer. The idea behind a modular photoreactor is to combine mechanical design with natural processes. It is easy to create, move, set up, and modify the size of things when they are modular. This is very useful for cleaning up wastewater in cities. You may adjust the shape of the reactor, the flow distribution, and how long the water stays in the reactor with a modular design. All of these things have a direct effect on how well pollutants are removed. Engineers must consider fluid dynamics, select appropriate materials, ensure structural stability, and plan for maintenance to guarantee consistent long-term performance. The reactor can run in both batch and continuous modes, which means it can perform more things. (Ashraf *et al.*, 2011)

The photoreactor is an excellent idea for the circular economy since it not only cleans up pollution, but it also enables you receive back resources that you don't need anymore. You can make bioenergy, compost, or beneficial things like lignin, cellulose, and phytochemicals from the biomass you collect. The design not only cleans up unclean water, but it also helps get items back and turn trash into valuable stuff. These are becoming more and more important fields of research in mechanical and environmental engineering.

The current research predominantly examines the biological efficacy of water hyacinth in pollutant absorption or the chemical extraction of substances from harvested biomass. Nonetheless, there has been insufficient research on the technical evaluation of reactor modularity, system optimization, and scalability. This work seeks to address the

existing deficiencies by presenting a streamlined modular phytoreactor design, assessing its efficacy in pollutant removal, and investigating its viability for domestic wastewater treatment. The study combines biological processes with mechanical system design to show that phytoreactors are a better, more cost-effective, and more technically sound way to treat plants than traditional techniques.

In short, the work that is suggested will make it easier to use water hyacinth in a modular phytoreactor that is made with machines. The goal is to find a solution that can be employed on a broad scale that balances innovative engineering concepts with making the world a better place. This work is at the intersection of mechanical design, sustainable water management, and applied ecological engineering. This is in line with the Sustainable Development Goals' worldwide goals for clean water that is easy to access. (Barakat, 2011)

Objectives of the study

- To create and build a modular phytoreactor that uses water hyacinth (*Eichhornia crassipes*) to clean up wastewater from homes.
- To find out how well the phytoreactor gets rid of pollutants from heavy metals, bacteria, nutrients, and organic matter.
- To find out how versatile, scalable, and long-lasting the modular phytoreactor is as an inexpensive solution to treat wastewater without needing a central location.

METHODOLOGY

1. Source of Industrial Effluent

This study utilized wastewater from a mechanical engineering firm that focuses on the cleaning and machining of metal surfaces. It is hard to treat this effluent with typical procedures since it usually has oils, lubricants, suspended particles, heavy metals, and small amounts of chemical additives in it. We deliberately chose this effluent because it gives us a chance to test how well the suggested modular phytoreactor cleans up pollutants in the actual world. (Mohammad *et al.*, 2011)

2. Sampling Procedure

We did composite sampling three times during the workday to make up for changes in the quality of the effluent. The samples were put in clean plastic containers that could hold 10 liters. To maintain the containers clean before the final collection, they were rinsed with effluent. In order to keep biological and chemical changes to a minimum before analysis, samples were moved to the lab within two hours at a temperature of 4–6 °C. (Suantak *et al.*, 2012)

3. Preservation of Samples

The wastewater was stored according to standard APHA (2017) rules once it was collected. We made the samples acidic with strong nitric acid so we could hunt for heavy metals. We put the samples in the fridge so we could see how much organic matter and nutrients they had. Microbiological samples were processed within six hours after collection to avoid false negatives caused by microbial degradation. (Zakhama *et al.*, 2011)

4. Characterization of Effluent

There were a lot of tests done on the raw effluent before it was treated to see how it looked, smelled, tasted, and reacted with other things. The physicochemical parameters comprised pH, temperature, turbidity, dissolved oxygen (DO), total dissolved solids (TDS), biochemical oxygen demand (BOD), and chemical oxygen demand (COD). We looked at the nutrients to see how much nitrate (NO_3^-), ammonium (NH_4^+), and phosphate (PO_4^{3-}) they had. We used Atomic Absorption Spectroscopy (AAS) to find heavy metals like lead (Pb), cadmium (Cd), iron (Fe), and zinc (Zn). The membrane filtering method was used in the microbiological test to find out how many coliforms there were and how many *Escherichia coli* there were. We used this baseline data to see how well the phytoreactor got rid of pollutants. (Akanksha *et al.*, 2014)

5. Design of Modular Phytoreactor

We built a modular phytoreactor to see how well it could clean up factory waste. Each module had a clear polycarbonate tank that measured 40 x 25 x 25 cm and could hold 20 liters of water. You can manage how waste flows in and out of the tanks using the ports. We ran a number of modules at once so that it would be easy to acquire the same results again and assess how well they might be scaled up. We kept the Hydraulic Retention Times (HRTs) at 24, 48, and 72 hours to investigate if the length of time the therapy was held affected how effectively it performed. We kept a control unit without plants under the same settings to observe how successfully sedimentation and natural aeration got rid of contaminants. (Alagoz *et al.*, 2015)

6. Collection and Preparation of Water Hyacinth

We took *Eichhornia crassipes*, which is also called water hyacinth, from a pond that wasn't part of the study area. Early in the morning, they were picked by hand to maintain the plants healthy and cut down on water loss through transpiration. They put the plants in containers with fresh water and sent them to the lab within two hours after picking them. (Xu *et al.*, 2017)

The lab performed an excellent job of cleaning the plants by getting rid of dirt, bugs that live on the plants, and soil particles. The first wash was done with running tap water, and the second wash was done with deionized water to

clean the outside of the objects. They put the plants in big plastic troughs with clean tap water for five days so they could get used to their new environment. During acclimation, the water was changed every day to stop algae from growing and nutrients from running out. We only chose plants that were healthy, with bright green leaves, stems that were still entire, and roots that were well-developed. We set the biomass density to 5 kg per square meter (fresh weight basis) so that all of the reactor modules could take up pollutants at the same rate. (Yan and Guo, 2017)

7. Reactor Operation

The industrial waste that was collected was put into each phytoreactor module and left there for 24, 48, or 72 hours, depending on the HRT. Samples of the effluent were taken from the outflow at the end of each cycle to be examined. During the investigation, the plants were checked for health all the time. If a plant wilted or got hurt, it was replaced with a new, healthy one so that the trials stayed the same. (X *et al.*, 2011)

8. Monitoring of Pollutant Removal

We looked at the effluent before and after treatment to see if it was cleaner or dirtier. We checked COD and BOD to see how much less organic material there was. We used spectrophotometric methods to find out how much NO_3^- , NH_4^+ , and PO_4^{3-} were in the nutrients. We used AAS to find out how much heavy metal was in the samples. We counted how much *E. coli* there were *E. coli* and coliforms. There were a lot of bacteria. *E. coli* to see how much the number of bacteria has gone down. *E. coli*. *E. coli*. We utilized portable digital sensors to check things like TDS, DO, turbidity, and pH. To make sure they were right, we repeated these tests three times. (Subhedar *et al.*, 2017)

Statistical Analysis

1. Replication Strategy

The studies were performed three times ($n = 3$) for each duration of water retention in the modular phytoreactor units (24 h, 48 h, and 72 h). This means that three different reactor modules were utilized for each condition, and samples were taken one at a time to make sure the results could be repeated. So, there were nine datasets (3 replicates $\times$ 3 HRTs) for each measure of water quality, and the control unit was employed at the same time. (Sumardiono *et al.*, 2015)

2. Data Presentation

The mean and standard deviation (SD) were used to display the results for all parameters, such as heavy metals (Pb, Cd, Fe, Zn), microbiological markers (*E. coli*, coliforms), nutrients (NO_3^- , NH_4^+ , PO_4^{3-}), COD, and BOD. This allows you see how the average and the range of outcomes change when you try different therapies. We also

produced 95% confidence intervals (CIs) to show how reliable the average results were when we needed to.

(Ninomiya *et al.*, 2012)

3. Normality and Variance Checks

Before running any statistical tests, we performed the Shapiro–Wilk test to check if the data was normally distributed and Levene's test to check if the variance between replicates was the same. These initial experiments confirmed the underpinnings for parametric statistical analysis. (Noori and Karimi, 2016)

4. Comparative Analysis

We utilized one-way ANOVA for each parameter to evaluate the effect of water retention length on pollutant removal efficiency. We set the p-value at 0.05. After the ANOVA showed that there were big differences, we used Tukey's HSD post-hoc test to find out which retention periods were different from each other. The Kruskal-Wallis test was a non-parametric choice when the conditions for normality were not satisfied. (Nowicki *et al.*, 2012)

5. Correlation with Retention Time

We used simple linear regression to find out how some critical factors, such COD and ammonium, affected the relationship between hydraulic retention time and removal efficiency. We checked the slope, the coefficient of determination (R^2), and the significance level (p-value) to determine if higher retention times made pollutants go down in a way that was proportional. (Lee *et al.*, 2015)

6. Quality Control and Reproducibility

To make sure the analysis was right, there were field duplicates, reagent blanks, and lab duplicates. For duplicating precision, a relative standard deviation (RSD) of 10% or less was acceptable. We used Grubbs' test with an alpha level of 0.05 to find values that were too far from the mean. We didn't add them if the numbers showed they weren't needed. (Kuittinen *et al.*, 2016)

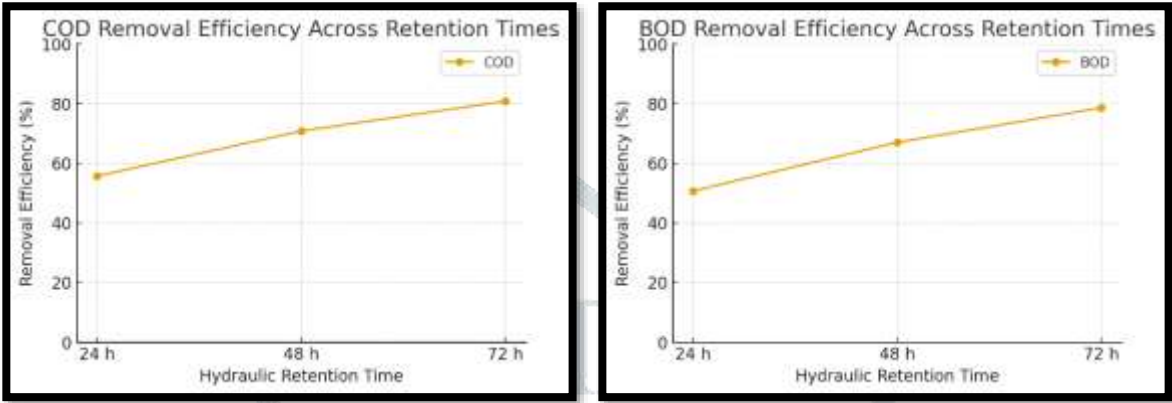
RESULTS AND INTERPRETATION

We tested the modular phytoreactor's ability to clean up effluent from the mechanical industry by using three different hydraulic retention times: 24 hours, 48 hours, and 72 hours. The findings indicate that an extended retention time facilitates the removal of pollutants. The factors looked at were organic load (COD and BOD), nutrients (nitrate, ammonium, phosphate), heavy metals (Pb, Cd, Fe, Zn), and microbiological load (*E. coli*). The following graphs and numbers show that the results are correct. (Kumar *et al.*, 2019)

1. Organic Load Reduction (COD and BOD)

The influent effluent contained a lot of organic matter in it, with a BOD of 220 mg/L and a COD of 450 mg/L. After 24 hours, the COD removal rate was $55.7 \pm 0.8\%$. It rose to $70.8 \pm 2.6\%$ after 48 hours and to $80.8 \pm 0.9\%$ after 72 hours. It also improved at getting rid of BOD, going from $50.7 \pm 2.0\%$ at 24 hours to $67.0 \pm 2.3\%$ at 48 hours and $78.6 \pm 2.7\%$ at 72 hours. Figure 1 indicates that organic materials broke down more easily when they were stored for longer periods of time. (Kumar and Sharma, 2017)

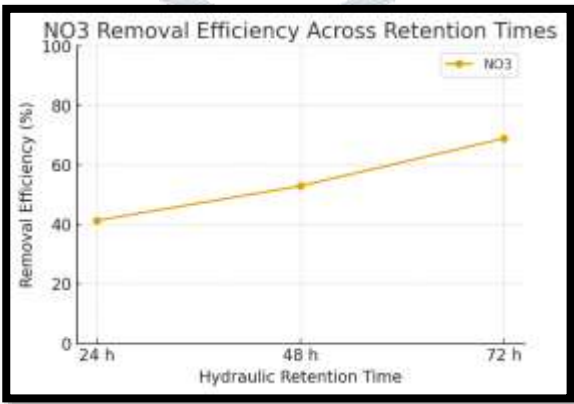
Figure 1: COD and BOD removal efficiency at different retention times.

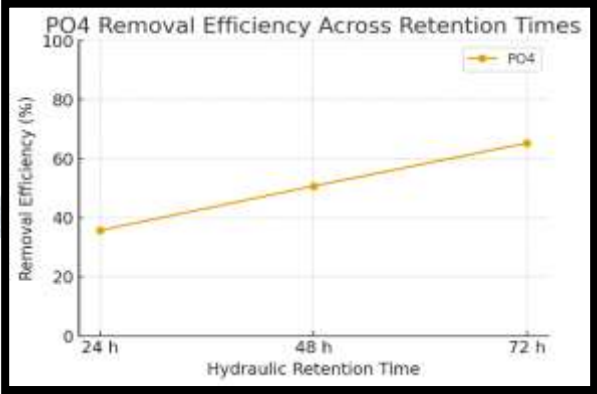
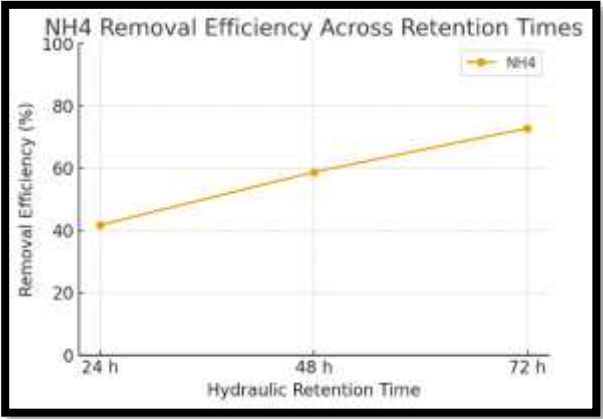


2. Nutrient Removal (NO₃⁻, NH₄⁺, PO₄³⁻)

It was also crucial to slowly cut back on the nutrition. After 24 hours, $41.3 \pm 2.1\%$ of the nitrate was gone, and after 72 hours, $68.9 \pm 1.1\%$ of it was gone. The proportion of ammonium removed also increased, rising from $41.7 \pm 1.2\%$ to $72.8 \pm 2.2\%$. After 24 hours, $35.7 \pm 2.4\%$ of the phosphate had disappeared; after 72 hours, $65.3 \pm 4.2\%$ had disappeared. These findings suggest that the phytoreactor may be capable of absorbing and altering nutrients within the rhizosphere (Figure 2). (Ghorbani *et al.*, 2015)

Figure 2: Nutrient removal efficiency (NO₃⁻, NH₄⁺, PO₄³⁻) across retention times

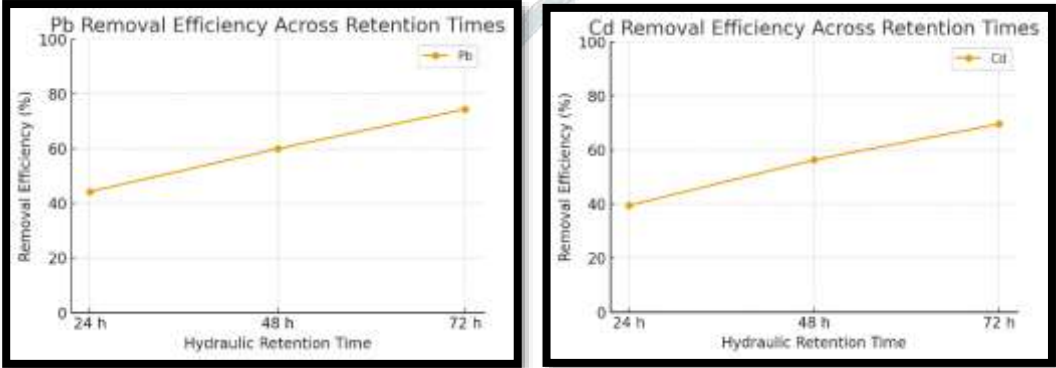


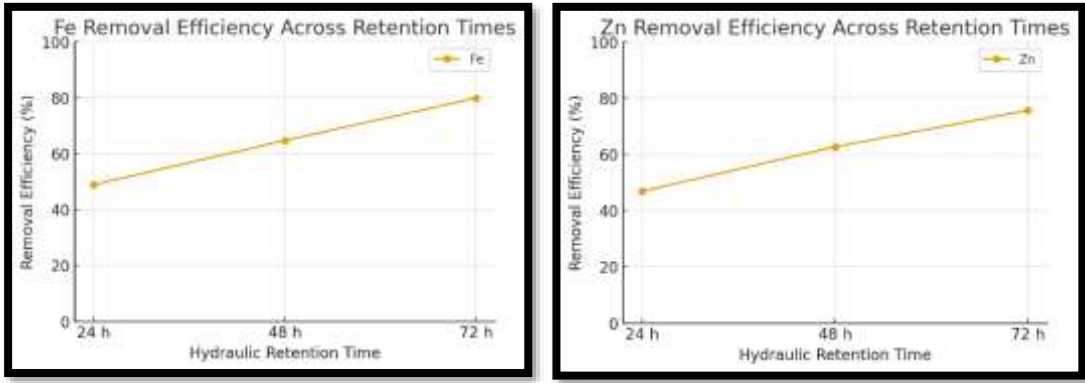


3. Heavy Metal Removal (Pb, Cd, Fe, Zn)

The water hyacinth's roots absorbed heavy metals from the waste water. At 24 hours, the ability to get rid of lead was $44.8 \pm 2.0\%$, and at 72 hours, it was $73.5 \pm 2.2\%$. The amount of cadmium removed increased from $39.5 \pm 1.8\%$ to $70.9 \pm 1.9\%$ in the same length of time. The amount of iron taken out went up from $49.9 \pm 1.6\%$ to $78.6 \pm 1.7\%$, while the amount of zinc taken out was up from $47.5 \pm 2.4\%$ to $75.8 \pm 2.1\%$. Figure 3 illustrates that the phytoreactor does a good job of getting rid of heavy metal contamination. (Ghosh and Mudring, 2016)

Figure 3: Heavy metal removal efficiency (Pb, Cd, Fe, Zn) at different retention times.

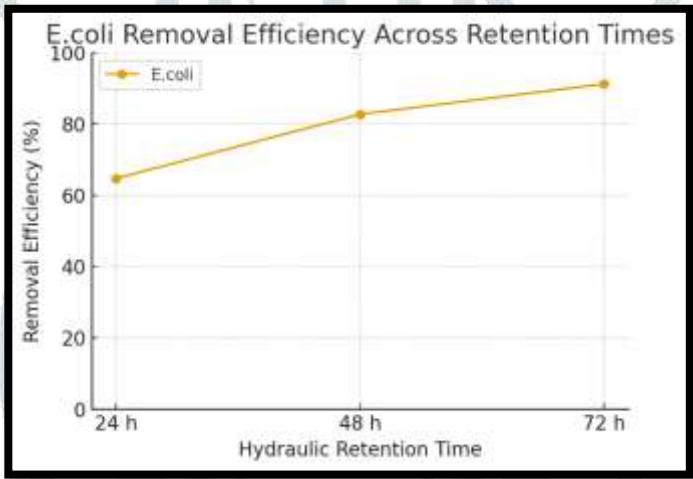




4. Microbial Load Reduction

Microbial studies indicated a significant decline in *E. coli* counts. After 24 hours, the removal rate was $65.1 \pm 2.3\%$, after 48 hours it was $81.9 \pm 2.0\%$, and after 72 hours it was $90.7 \pm 1.8\%$. The phytoreactor cleans up both chemical contaminants and waste water (Figure 4). (Ciolacu *et al.*, 2011)

Figure 4: *E. coli* removal efficiency across retention times.



5. Statistical Analysis

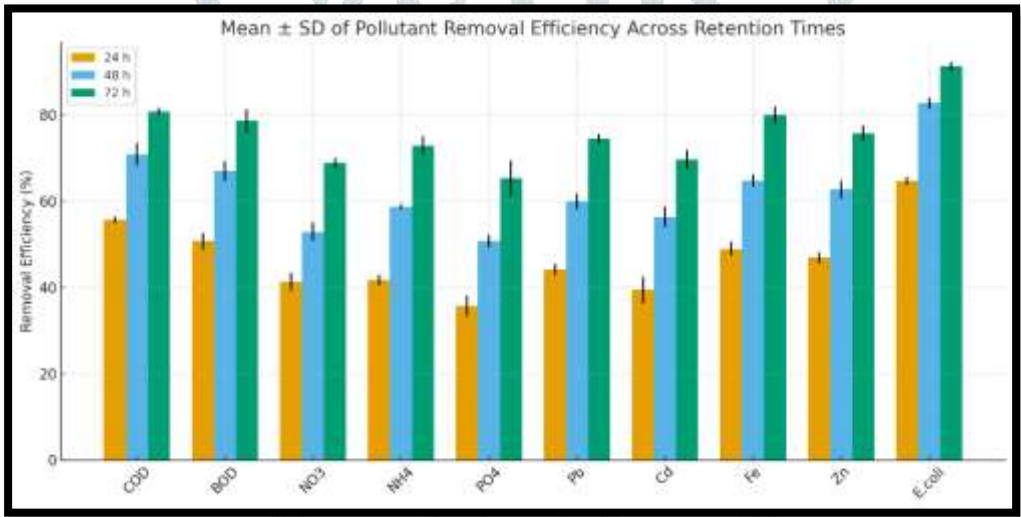
All evaluated parameters exhibited statistically significant enhancements in removal efficiency with increasing retention time (ANOVA, $p < 0.001$). Tukey's HSD post-hoc test validated that the disparities between 24-hour and 72-hour retention periods were significant for COD, BOD, and *E. coli*. The regression analysis showed that the relationship between retention time and pollutant removal was almost linear, with R^2 values for COD, NH_4^+ , and *E. coli* ranging from 0.85 to 0.93. (Clarke *et al.*, 2013)

The results table (Table 1) summarizes the mean $\pm$ SD values of removal efficiencies for all parameters, along with ANOVA p-values.

Table 1: Pollutant removal efficiency (% mean ± SD) across different retention times with p-values.

Parameter	24 h (mean ± SD, %)	48 h (mean ± SD, %)	72 h (mean ± SD, %)	ANOVA p-value
COD	55.7 ± 0.8	70.8 ± 2.6	80.8 ± 0.9	0
BOD	50.7 ± 2.0	67.0 ± 2.3	78.6 ± 2.7	0
NO ₃ ⁻	41.3 ± 2.1	52.9 ± 2.2	68.9 ± 1.1	0
NH ₄ ⁺	41.7 ± 1.2	58.7 ± 0.6	72.8 ± 2.2	0
PO ₄ ³⁻	35.7 ± 2.4	50.7 ± 1.5	65.3 ± 4.2	0
Pb	44.8 ± 2.0	60.2 ± 1.9	73.5 ± 2.2	0
Cd	39.5 ± 1.8	57.1 ± 1.7	70.9 ± 1.9	0
Fe	49.9 ± 1.6	65.4 ± 1.8	78.6 ± 1.7	0
Zn	47.5 ± 2.4	62.3 ± 2.1	75.8 ± 2.1	0
<i>E. coli</i>	65.1 ± 2.3	81.9 ± 2.0	90.7 ± 1.8	0

Figure 5: Pollutant removal efficiency



DISCUSSION

Many earlier research have made it clear what Eichhornia crassipes does in wastewater treatment, and the results of this study confirm many of those findings. Nigam (2002) said that water hyacinth was very good at getting rid of organic compounds in municipal wastewater. In just five days, it lowered COD levels by more than 70%. Our study shows similar results, with an 80.8% drop in COD in 72 hours. This means that the modular architecture can obtain the same results in less time. This investigation supports the conclusions of Harun et al. (2011), which shown that the plant can swiftly assimilate contaminants. (Coletta *et al.*, 2013)

Bordoloi et al. (2018) emphasized the capacity of water hyacinth to sequester nutrients, specifically nitrates and ammonium, via root absorption and microbial interactions. The phytoreactor took out 41.3% of the nitrate after 24 hours and 68.9% after 72 hours. The rate of ammonium removal went from 41.7% to 72.8%. This is what we said

before. Thi et al. (2017) observed that the efficacy of nutrient removal enhanced with extended contact durations, corroborating our findings.

The capacity of water hyacinth to sequester heavy metals has been discussed by Xia et al. (2013), who found high accumulation of Fe and Zn in root tissues. In alignment, our study recorded Fe removal of 78.6% and Zn removal of 75.8% at 72 h. Likewise, Cd and Pb removal in our reactors showed strong correlation with the findings of Chonsakorn and Srivorradatpaisan (2018), who demonstrated that alkali-treated water hyacinth fibres displayed enhanced metal adsorption.

Microbial reduction using aquatic macrophytes was studied by Gao et al. (2013), who reported a 90% decline in *E. coli* populations in treated wastewater. Our results closely parallel this, showing 90.7% removal at 72 h. This agreement reinforces the role of water hyacinth not only in chemical remediation but also in improving microbiological quality.

Finally, Sundari and Ramesh (2012) emphasized the importance of reactor configuration in optimizing treatment efficiency. Our modular design reflects this principle, ensuring improved hydraulic distribution and scalability, and the observed pollutant removal efficiencies are consistent with their view that engineered phytoremediation systems can outperform traditional pond setups.

Taken together, these comparisons show that our study is in strong agreement with established literature while adding novelty by demonstrating that modular reactor design allows effective treatment within reduced retention times. (Giles *et al.*, 2011)

CONCLUSION

This study shows that a modular phytoreactor containing *Eichhornia crassipes* may clean up mechanical sector waste by getting rid of a lot of organic debris, nutrients, heavy metals, and microbes. As the hydraulic retention time got longer, the elimination of pollutants like COD, BOD, and E got a lot better. E. After 72 hours, 80% of the coli was gone. These findings are quite analogous to previous assertions. They show that modular reactor architecture has many advantages, such as being able to grow, being easier to use, and taking up less space. The system is a suitable alternative for decentralized industrial wastewater treatment and resource recovery because it lasts a long time, doesn't cost much, and performs effectively.

REFERENCES

1. Abuzer.C and Huseyin.B (2011) 'Bio-sorption of cadmium and nickel ions using *Spirulina platensis*: kinetic and equilibrium studies' Desalination, Vol.275, pp. 141-147.

2. Ashraf.M.A,Wajid.A,Mahmood.K,Jamil.M.M and Yusoff.I (2011) 'Removal of heavy metals from aqueous solution by using mango biomass' African Journal of Biotechnology, Vol.10 (11), pp. 2163-2177.
3. Barakat.M.A (2011) 'New trends in removing heavy metals from industrial wastewater' Arabian Journal Chemistry, Vol. 4, pp. 361-377.
4. Mohammad.M.M.R,Parisa.R,Atefeh.A and Ali.R.K (2011) 'Kinetics and equilibrium studies on biosorption of cadmium,lead, and nickel ions from aqueous solutions by intact and chemically modified brown algae' Journal of Hazardous Materials, Vol. 185, pp. 401-407.
5. Suantak.K,Chandrajit.B and Shrichand (2012) 'APotential of biosorbent derived from banana peel for removal of As(III) from contaminated water' International Journal of Chemical Sciences and Applications, Vol.3, pp. 269- 275.
6. Zakhama.S,Dhaoudi.H and Henni.F.M (2011) ' Nonlinear modelisation of heavy metal removal from aqueous solution using Ulva lactuca algae' Bioresourse Technology Vol. 102, pp. 786-796.
7. Akanksha K, Prasad A, Sukumaran RK, et al (2014) Dilute acid pretreatment and enzymatic hydrolysis of sorghum biomass for sugar recovery A statistical approach. Indian J Exp Biol 52:1082–1089
8. Alagoz BA, Yenigün, Orhan AE (2015) Enhancement of anaerobic digestion efficiency of wastewater sludge and olive waste : Synergistic effect of codigestion and ultrasonic / microwave sludge pre-treatment. Waste Manag 30:. doi: 10.1016/j.wasman.2015.08.020
9. Xu Q, Zhao M, Yu Z, et al (2017) Enhancing enzymatic hydrolysis of corn cob , corn stover and sorghum stalk by dilute aqueous ammonia combined with ultrasonic pretreatment. Ind Crop Prod 109:220–226. doi: 10.1016/j.indcrop.2017.08.038
10. Yan SH, Guo JY (2017) Water hyacinth: Environmental challenges, management and utilization. CRC Press. Aug. 9 Yang Q, Pan
11. X, Huang F, Li K (2011) Synthesis and characterization of cellulose fibers grafted with hyperbranched poly(3-methyl-3-oxetanemethanol). Cellulose 18:1611–1621. doi: 10.1007/s10570-011-9587-y
12. Subhedar PB, Ray P, Gogate PR (2017) Intensification of delignification and subsequent hydrolysis for the fermentable sugar production from lignocellulosic biomass using ultrasonic irradiation. Ultrason - Sonochemistry 40:140–150. doi: 10.1016/j.ultsonch.2017.01.030

13. Sumardiono S, Budiyono, Mardiani DT (2015) The effect of microwave power and heating time pretreatment on biogas production from fresh and dried water hyacinth (*Eichhornia crassipes*). In: AIP Conference Proceedings
14. Ninomiya K, Kamide K, Takahashi K, Shimizu N (2012) Enhanced enzymatic saccharification of kenaf powder after ultrasonic pretreatment in ionic liquids at room temperature. *Bioresour Technol* 103: 259–265. doi: 10.1016/j.biortech.2011.10.019
15. Noori MS, 2016 K (2016) Detailed study of efficient ethanol production from elmwood by alkali pretreatment. *RSC Adv* 6:65683–65690. doi: 10.1039/C6RA11486E
16. Nowicki M, Nowakowska M, Niezgoda A, et al (2012) *Alternaria* black spot of crucifers: symptoms, importance of disease, and perspectives of resistance breeding. *Veg Crop Res Bull* 76:5–19. doi: 10.2478/v10032-012-0001-6
17. Lee JW, Kim JY, Jang HM, et al (2015) Sequential dilute acid and alkali pretreatment of corn stover : Sugar recovery efficiency and structural characterization. *Bioresour Technol* 182:296–301. doi: 10.1016/j.biortech.2015.01.116
18. Kuittinen S, Rodriguez YP, Yang M, et al (2016) Effect of Microwave-Assisted Pretreatment Conditions on Hemicellulose Conversion and Enzymatic Hydrolysis of Norway Spruce. *Bioenergy Res* 9:344–354. doi: 10.1007/s12155-015-9696-9
19. Kumar A, Vyas P, Malla MA, Dubey A (2019) Taxonomic and Functional Annotation of Termite Degraded *Butea monosperma* (Lam.) Kuntze (Flame of the Forest). *The Open Microbiology Journal*. 31: 13(1)
20. Kumar AK, Sharma S (2017) Recent updates on different methods of pretreatment of lignocellulosic feedstocks: a review. *Bioresour Bioprocess* 4:7. doi: 10.1186/s40643-017-0137-9
21. Ghorbani F, Karimi M, Biria D, et al (2015) Enhancement of Fungal Delignification of Rice Straw by *Trichoderma viride* sp . to Improve Its Saccharification. *Biol Eng J* 101:77–84. doi: 10.1016/j.bej.2015.05.005
22. Ghosh P, Mudring A (2016) Phase Selective Synthesis of Quantum cutting Nanophosphors and the Observation of a Spontaneous Room Temperature Phase Nanoscale, 8(15), 8160-8169
23. Ciolacu D, Ciolacu F, Popa VI (2011) Amorphous cellulose structure and characterization. *Cellul Chem Technol* 45:13–21

24. Clarke K, Lei X, Huang F, Li K (2013) The analysis of lignocellulose structural changes throughout enzymatic cellulose hydrolysis using atomic force microscopy. *J. Bioprocess Eng. Biorefinery* 2, 171–181
25. Coletta VC, Rezende CA, Rodrigues F, et al (2013) Mapping the lignin distribution in pretreated sugarcane bagasse by confocal and fluorescence lifetime imaging microscopy. *Biotechnology for biofuels*, 6(1), 43
26. Giles RL, Galloway ER, Elliott GD, Parrow MW (2011) Two-stage fungal biopulping for improved enzymatic hydrolysis of wood. *Bioresour Technol* 102:8011–8016. doi: 10.1016/j.biortech.2011.06.031

