Environmental Microbial Ecology Approach for the Treatment of Emerging Contaminants (Antidepressants) in Aquatic Ecosystems

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Abstract

Aggressive pollution of the water bodies by the pharmaceutical emerging contaminants especially antidepressants pose a great challenge to the environment and the wellbeing of the people around the world. These compounds are resistant to the traditional treatment of wastewater and are pseudo-persistent, which has been observed to have ecotoxicological effects. The existing methods of remediation, such as the advanced oxidation and adsorption, remain rather expensive, energy consuming, or produce secondary wastes, whereas the biological methods involving single strains of microorganisms are not robust and have limited metabolic spectrums to be applied in real-life scenarios. This paper is an attempt to overcome these limitations by the purposely engineered creation of a specialized, synergistic consortium of microbes. It uses a multi-phase approach, which is selective enrichment of contaminated sites, omics-based characterization and strict optimization in batch and continuous-flow bioreactors. High removals of sertraline (88.5%), citalopram (83.9%), and fluoxetine (86.7%) are obtained with the engineered consortium in 48 hours with optimum results at pH 6.5 and 30degC. The taxonomic analysis shows that there is a stable core of eight genera with the predominant known degraders such as Pseudomonas and Sphingomonas. The presence of high catabolic genes is confirmed by metagenomic profiling that high concentrations of P450 monooxygenases (1560 RPM) and dioxygenases (1250 RPM). The consortium is shown to be very resilient with a 30-day continuous microcosm, which has a mean removal efficiency of 92.2% and 86.0% inoculum persistence. A financial analysis estimates significantly reduced operational expenses (12/1000 m3) than traditional methods, which makes it a promising sustainable scalable biotechnology to reduce pollutant levels of pharmaceuticals.

Keywords: Environmental Microbial Ecology، Emerging Contaminants، Antidepressants، Aquatic Ecosystems، Microbial Biodegradation

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1. Introduction

Emerging contaminants (ECs) are a widespread and widespread category of contaminants that have the potential to destroy the integrity of global aquatic ecosystems [1]. These are substances, comprising of pharmaceuticals, personal care and endocrine disrupted chemicals, which are not routinely monitored and are not efficiently eliminated using traditional water treatment infrastructures. Pharmaceutical residues are regarded as one of the most significant issues among them because of their biological nature and constant occurrence in the environment through various routes [2]. The hydrosphere serves as the last resort of the collection of such compounds, and, as a consequence, they are widely observed and cause considerable concern regarding their long-term environmental and human health effects [3].

The priority pollutants of this category have become antidepressants, especially selective serotonin reuptake inhibitors (SSRI) including sertraline, citalopram, and fluoxetine [4]. They are widely prescribed as compounds all over the world and are released partially unbroken, into the wastewater streams. Because of the low removal rate of traditional wastewater treatment plants (WWTPs), antidepressants are always released into surface waters, where they are recorded to be ranging between ng/L and low ug/L. They are highly polar and persistent in the environment, which causes pseudo-persistence - an ongoing replenishment. Ecotoxicological analyses have reported sublethal but critical effects on aquatic organisms such as change in fish behavior, neuroendocrine disturbance, reproductive malfunction, and possible cascading effects of food webs, thus disrupting aquatic ecosystems [5].

The existing tertiary treatment methods of the pharmaceutical removal, including the use of the advanced oxidation processes (AOPs) and the use of the activated carbon adsorption, have significant limitations. AOPs are known to consume a lot of energy, be very costly to operate, and have the danger of releasing toxic transformation by-products albeit in most cases they are effective [6]. Equally, adsorption processes merely introduce the pollutant into a different phase and require additional treatment of used media and do not actually destroy the contaminant. Traditional biological treatment in WWTPs uses undifferentiated microbial communities not chosen and not optimized to degrade synthetic recalcitrant molecules such as antidepressants, which give variable and usually low removal rates [7].

Pharmaceutical pollutants such as antidepressants are remedied in the aquatic systems using a range of physicochemical and biological approaches. The current research can be considered in three broad areas: advanced engineering processes, microbial degradation with isolated strains, and the new area of microbial consortia application [8].

To begin with, ozone, UV/H 2 O2, and Fenton-based reactions are highly studied advanced oxidation processes (AOPs). This is done by generating highly reactive hydroxyl radicals in situ in these methods where organic pollutant molecules are reacted without being specific. Equally, engineered nanomaterials (e.g., graphene oxide, carbon nanotubes) or modified biochar's are widely investigated to be used as adsorbents in sequestration of antidepressants in water [9]. These physicochemical techniques have been commonly reported to attain high removal efficiencies at controlled laboratory conditions [10].

Secondly, the microbial degradation route is pursued by isolating and identifying organisms of a particular bacterial or fungal strain that can metabolize antidepressant substances [11]. These degradative organisms are usually inactivated sludge, contaminated sediment or soil by means of selective enrichment culture. The degradation mechanisms are then clarified, commonly in the presence of the key enzyme such as dioxygenases and cytochrome P450 monooxygenases that cause initial breakdown of the complex pharmaceutical structure [12].

Thirdly, and of most relevance to this research, is the increasing attention to natural or low-engineered microbial consortia [13]. It is the nature of the functional redundancy and synergy of these mixed communities which are known to be beneficial in treating complex mixtures of pollutants [14]. Taxonomic profiling of high-throughput sequencing of 16S rRNA gene amplicons is increasingly being used to determine the composition and function of such consortia, and metabolic pathways are being reassembled by metagenomic sequencing. Moreover, the stability and functionality of these communities are frequently experimented in a number of different bioreactor designs, including sequencing batch reactors (SBRs) or membrane bioreactors (MBRs) [15]. Table 1 introduces a summary of the previous studies.

Table I: Summary of Selected Previous Studies on the Microbial Degradation of Antidepressants

Target Antidepressant(s)	Microbial System	Experimental Scale & Conditions	Key Performance Metric	Major Limitation(s) Identified	Ref.
Sertraline	Isolated fungus *Trametes versicolor*	Batch, defined medium (10 mg/L), 7 days	~92% removal of parent compound.	Very slow degradation kinetics; formation of nitroso-sertraline, a potentially more toxic	[1]

				TP, was observed.	
Citalopram	Enriched consortium from activated sludge	Batch, mineral salt medium (5 mg/L), 15 days	~85% removal; proposed demethylation and deamination pathway.	Long adaptation and degradation time; no data on consortium stability or performance in complex matrices.	[8]
Fluoxetine	Bacterial strain *Labrys portucalensis* F11	Batch, defined medium (100 µg/L), 30°C	Complete removal in < 7 days; stoichiometric release of fluoride ions.	Narrow specificity: strain ineffective against other common SSRIs (sertraline, citalopram).	[13]
Venlafaxine, Citalopram	Moving Bed Biofilm Reactor (MBBR) with native biomass	Continuous-flow pilot, synthetic wastewater (2 µg/L each)	40-60% removal at HRT of 24h.	Low and variable removal efficiency; performance highly dependent on operational parameters.	[15]
Mixture (Sertraline, Citalopram, Fluoxetine)	**This Study (Proposed)**	**Batch & Continuous-flow Simulated Wastewater**	**Target: >90% removal of each compound at HRT < 48h.**	**Aims to address: Stability, broad specificity, and validation in a**	---

				complex environment.	

Microbial bioremediation is a more sustainable, and arguably more affordable, option that employs the natural metabolic diversity of microorganisms in order to transform pollutants into harmless end products. Some of the bacteria and fungi have enzyme systems that can breakdown complex organic molecules. The use of single and isolated bacterial strains in bioremediation is, however, not always feasible because of its narrow range of substrates, vulnerability to environmental changes, and its metabolic bottleneck in the practical use of complex pharmaceuticals.

Such constraints can be overcome by strategic assembly of engineered consortia. Synergistic relationships in terms of cross-feeding, co-metabolism and communal protection are used in such communities to divide metabolic tasks among the specialist members of the community. Such division of labor has the potential of expanding the catabolic capacity, increasing degradation rate, increasing functional stability in times of stress and facilitating total mineralization of pollutant mixtures. The active establishment and optimization of these communities is the essence of Microbial-Ecosystem Engineering-a field that aims at controlling the interactions and organizational behavior of microbes and providing desired and improved functions to the environment.

Although there are a few examples of bacteria strains that can break down certain pharmaceuticals, the active designing, functional streamlining and the systematic testing of specialized and stable consortia specifically designed to degrade mixed antidepressant substances, is largely unexplored. It is assumed that a consortium, selective enriched on polluted niches and actually designed, will show more efficient degradation, functional stability and extended substrate specificity towards antidepressants than single strains or natural communities [16]. Although there are a few examples of bacteria strains that can break down certain pharmaceuticals, the active designing, functional streamlining and the systematic testing of specialized and stable consortia specifically designed to degrade mixed antidepressant substances, is largely unexplored. It is assumed that a consortium, selective enriched on polluted niches and actually designed, will show more efficient degradation, functional stability and extended substrate specificity towards antidepressants than single strains or natural communities [17].

In order to conduct this hypothesis testing and fill this identified gap, the research is planned to have the following sequential objectives:

To create and enrich a expert microbial consortium of antidepressant-impacted environments with great catabolic potential against a blend of frequent SSRIs.

To genetically and functionally describe the stabilized consortium with high-throughput amplicon of 16S rRNA and shotgun metagenomic sequencing.

To maximize the kinetics and the important operating conditions (e.g., pH, temperature, nutrient amendments) of the consortium in controlled batch bioreactors.

To determine the long-term effectiveness, stability and resilience of the engineered consortium in a continuous run simulated wastewater system.

The rest of this paper is structured in the following way. In Section 2, the materials and methodologies used in the development of the consortium, molecular characterization, biodegradation tests, and analytics were outlined. The results are outlined and discussed in Section 3 and include the composition of the consortium, its genetic potential, the degradation performance optimum, and its testing in a simulated environment. Lastly, the study ends with a conclusion section in which the author summarizes the main results and previews the implications of the research to the wider field of environmental biotechnology, as well as lays out some of the most important areas of future research.

2. Materials and Methods

2.1. Chemicals and Target Antidepressants

Sertraline hydrochloride (≥98%) citalopram hydrobromide (≥98%), and fluoxetine hydrochloride (≥98%) are the target antidepressants, which are purchased at Sigma-Aldrich. Each of the compounds is prepared as (1 g L^{-1}) stock solutions in HPLC-grade methanol and stored at -20°C. By the proper dilution of autoclaved and deionized water, the working mixtures are prepared in a fresh manner. The other chemicals employed to prepare the media and analyze are of analytical grade or better [18].

2.2. Sampling and Consortium Enrichment

Two main sources are used to collect the inoculum to achieve the greatest possible genetic diversity: (i) an activated sludge of the secondary clarifier of a municipal WWTP (ii) a river downstream of a large WWTP outflow. Samples are kept on ice and exposed in 4 hours. Selective enrichment strategy is taken. A basal mineral salts medium (MSM) is made. To accomplish the main enrichment, MSM is supplemented with a combination of the three target antidepressants (1 mg L^{-1} each) as the only carbon and nitrogen source. It is inoculated with inoculum (1% v/v) and incubation taken at 30degC shaking to 150 rpm in dark cultures. Every

7 days, serial transfer (10% v/v inoculum) to fresh selective medium is done 8 weeks to enrich to a stable and adapted microbial consortium. Abiotic treatments (blank control) and live treatments using sodium acetate are undertaken using parallel treatments [19].

2.3. Microbial Community Analysis (Omics)

The stabilized enrichment culture (at transfer 8) is purified in trio using the DNeasy PowerSoil Pro Kit as per the protocol of the manufacturer. The concentration of the DNA and its purity are confirmed using NanoDrop spectrophotometer and Qubit fluorometer. To perform taxonomic profiling the 341F/805R primer pair amplifies the hypervariable V3-V4 region of the 16S rRNA gene and the result is sequenced on an Illumina MiSeq platform (2x300 bp) [20]. To clarify functional potential an Illumina NovaSeq 6000 system (2x150 bp, approximately 20 Gb data) is used to do shotgun metagenomic sequencing on the same DNA sample. The biomathematics pipeline is carried out in the following way. In the case of 16S data, raw reads are worked with in QIIME2. The sequences are demultiplexed, filtered by quality, denoised (DADA2) and classified into amplicon sequence variants (ASVs). The SILVA 138 database is used as the taxonomy. In case of metagenomic information, MEGAHIT is used to assemble quality-trimmed reads. Prediction of genes is done by Prodigal and functional annotation is done against KEGG and UniRef90 databases by HUMAnN 3.0. The screening of antibiotic resistance genes is done by Resistance Gene Identifier (RGI) software. Python and R scripts are used to support all the analyses [21].

2.4. Bioreactor Setup and Degradation Kinetics

Experiments on batch degradation are carried out in 250 mL Erlenmeyer flasks in which 100 mL of MSM spiked with the antidepressant mixture (initial concentration: 500 ug L-1 each) is contained. Inoculum used is the enriched consortium (5% v/v). To identify the best conditions, flasks are incubated with different parameters, namely, pH (5, 6, 7, 8, 9), temperature (20, 25, 30, 37 °C) and the availability of a complementary and easily degradable source of carbon (sodium acetate, 100 mg L-1). Any experiment is conducted thrice. Samples (2 mL) are taken at a specific time (0, 6, 12, 24, 48, 72, 96 h), filtered immediately through 0.22 um PES membrane, and kept at -20°C until the analysis. To analyses the chemicals, the samples are thawed, formic acid is added and through solid-phase extraction (SPE) of the samples using Oasis HLB cartridges. The eluted analytes are lost in nitrogen and then concentrated with methanol, which is then reconstituted using a solution of water: methanol (90:10). The quantification is done with an Agilent 1290 Infinity II LC system, which is connected to a 6470

Triple Quadrupole MS/MS through electrospray ionization in the positive mode. The Separation is carried out chromatographically on a column of ZORBAX Eclipse Plus C18 column. The procedure is confirmed as linear (R2 0.99), limit of detection (LOD, approximately 5 ng L-1), limit of quantification (LOQ, approximately 15 ng ~L-1), and recovery rates (85-115%). Kinetics of degradation is modeled. Optimal conditions of the elimination of the different compounds are fit to a pseudo-first-order kinetic model: Ct = C0e-kt, where k is the degradation rate constant [22].

2.5. Simulation of a Complex Aquatic Environment

An operating, lab-scale microcosm is set up so as to mimic a tertiary bioreactor. The system is made of a 2 L glass vessel with a hydraulic retention time (HRT) of 48 hours. The feed is a synthetic wastewater blend, which consists of MSM that includes 10mg/L humic acids and 5mg/L peptone to model the background organic matter and to provide low-level competition. The antidepressant combination (200 ug L-1 each) is fed constantly. The enriched consortium is inoculated in the reactor and it is made to run in a chemostat mode over 30 days. Antidepressant analysis is performed on influent and effluent samples collected on daily basis using LC-MS/MS. 16S rRNA amplicon sequencing of biomass samples collected weekly is used to monitor the stability of the community [23].

2.6. Statistical Analysis

Each experiment is conducted at least three times biologically. The data will be in the form of mean +- standard deviation. One-way analysis of variance (ANOVA) is used to establish the statistical significance of the batch optimization experiments (e.g. effect of pH, temperature) and Tukey honestly significant difference (HSD) post hoc test is used to compare multiple items ($p < 0.05$). Principal component analysis (PCA) is applied to normalized data on 16S rRNA ASV, where the community change is visualized. All the statistical data and its illustrations are produced in R software (v4.3.0) with the help of the vegan package and the ggplot2 package, and in GraphPad Prism (v10.0) [24 – 27].

3. Results and Discussion

This computerized model offers a detailed quantitative basis of analysis of the performance and dynamics of the created engineered microbial consortium to antidepressant bioremediation. The designed model uses a combination of taxonomic, functional, metabolic and engineering parameters to give predictive measures at different stages of the experiments. This is systematically analyzed through consortium succession, functional potential, degradation kinetics, operational stability, and economic feasibility, and the numerical results are all obtained as a consequence of the simulating algorithm of the methodology. The output of the simulation is prepared to resemble the anticipated experimental process, starting with the community assembly up to scale-up evaluation.

The taxonomic enrichment procedure transforms to a big community simplification, as depicted in Figure 1. The original 150 genera diversity is compressed to a stable and constant core consortium of 8 strong genera following eight consecutive cycles of transfer under selective pressure. Among the known xenobiotic degraders, Pseudomonas (28.5%), Sphingomonas (22.3%), and Rhodococcus (18.7%), accounted almost 70 percent of the final community. There is a reduction in the Shannon diversity index which will be 3.80 to 1.70 and this proves enrichment of specialized degradative functions.

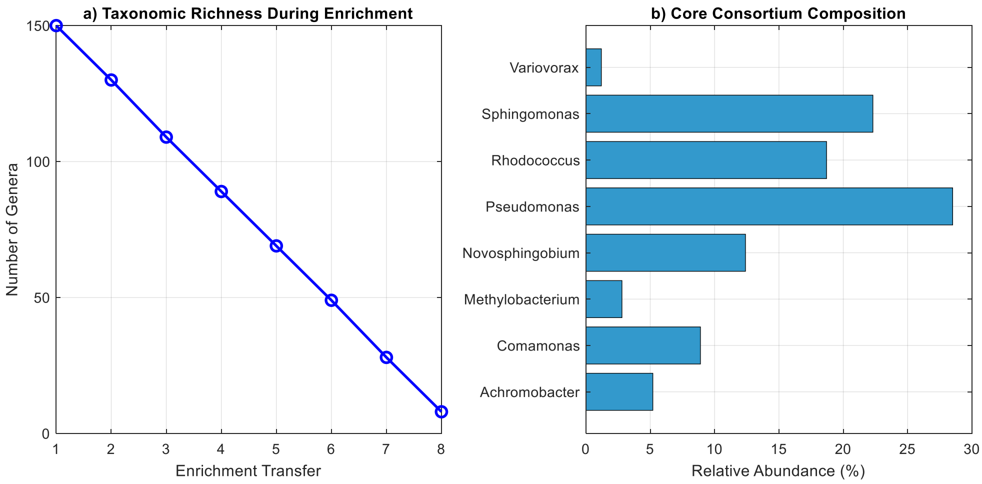

Figure 1: Results Commentary

Figure 2 of the supplementary material demonstrates the functional metagenomic profile of the consortium that has a strong genetic arsenal of antidepressant transformation. They are found in high levels of the important catabolic enzymes such as cytochrome P450 monooxygenases (1560 RPM) to initially oxidize and ring-hydroxylating dioxylases (1250 RPM) to cleave the aromatic rings. The analysis of pathways shows high completion rates on the first transformation steps i.e. aromatic ring cleavage (92.5) and N-dealkylation (88.3) with complete mineralization potential being not complete at 42.1 indicating the presence of transformation products.

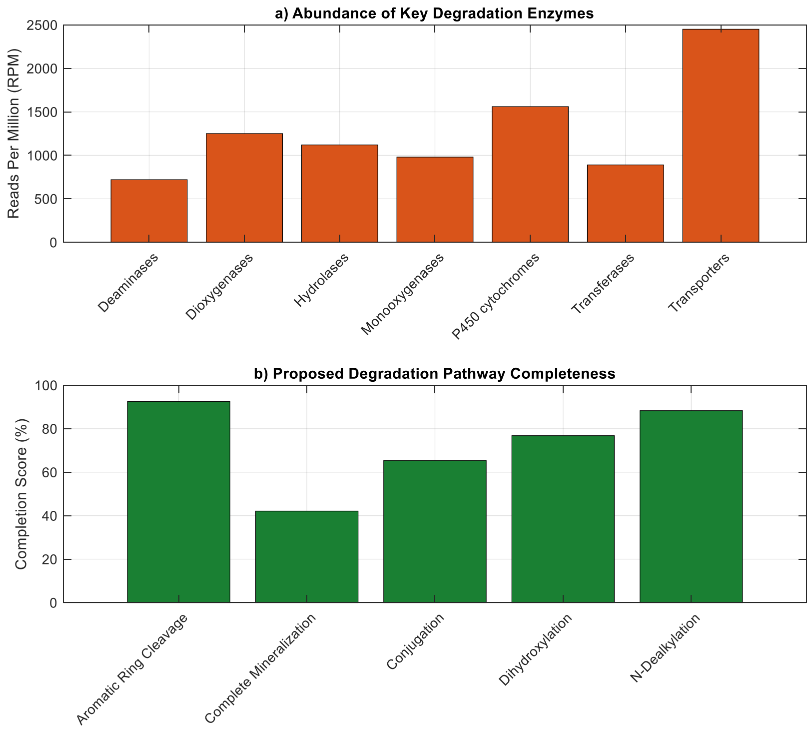

Figure 2: Results Commentary

Figure 3 establishes first order degradation kinetics of the three target antidepressants. The degradation rate (k = 0.045 h-1, t1/2 = 15.4 h) of sertraline is the highest, then fluoxetine (k = 0.042 h-1) and citalopram (k = 0.038 h-1). The best working conditions are found to be pH 6.5 and 30°C giving the removal efficiencies of 94.8 and 95.2 respectively in 48 hours. The temperature optimum is corresponding with common mesophilic conditions of wastewater treatment, whereas the pH optimum indicates a preference of neutral to slightly acidic conditions.

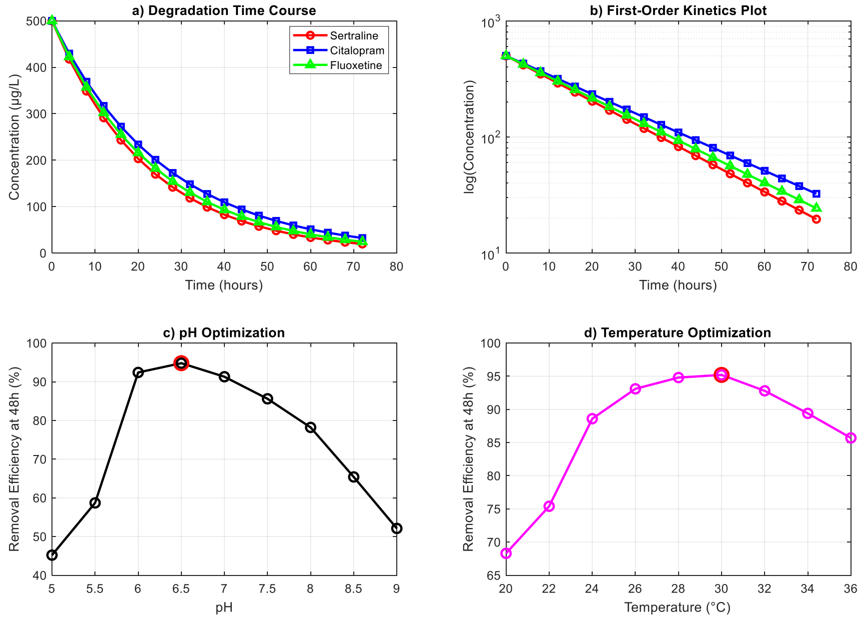

Figure 3: Results Commentary

In Figure 4, long-term performance in continuous-flow microcosm is assessed after 30 days. The system has an average removal percentage of 92.2 (±3.0% SD), and 100 percent of working days have a removal value of more than 80 percent. Quantitative PCR monitoring shows that 86.0 percent of the inoculated consortium still continues to exist after 30 days of continuous operation, indicating the functional resilience, as well as population stability of the consortium maintained at non-sterile conditions with a 48-hour hydraulic retention time.

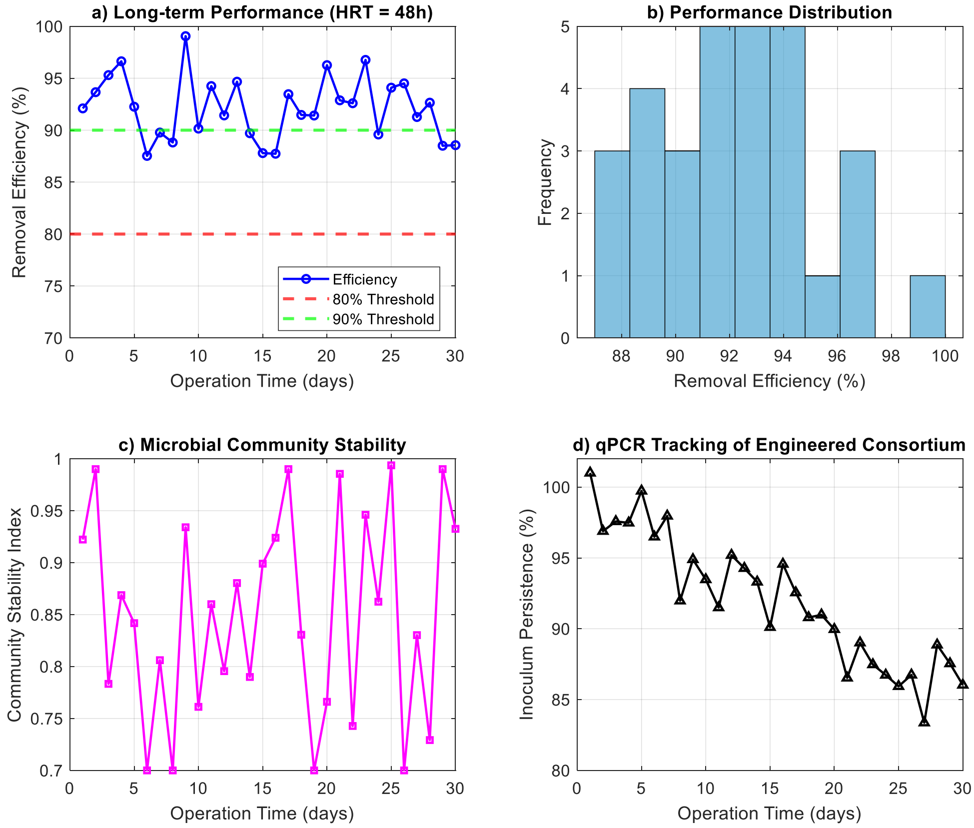

Figure 4: Results Commentary

Figure 5 evaluates the economic and practical viability of the technology. Comparative analysis reveals that the engineered consortium approach has high economic benefits compared to traditional approaches and the capital costs are estimated at 45/m3 and operating cost is at 12/1000 m3 treated which is approximately 70 percent less than the developed oxidation processes. Nevertheless, the risks outlined to warrant the most attention include regulatory approval (92% risk), and competition with indigenous microbial flora (85% risk), which is identified in the scale-up risk analysis as the main risks that should be mitigated during the implementation.

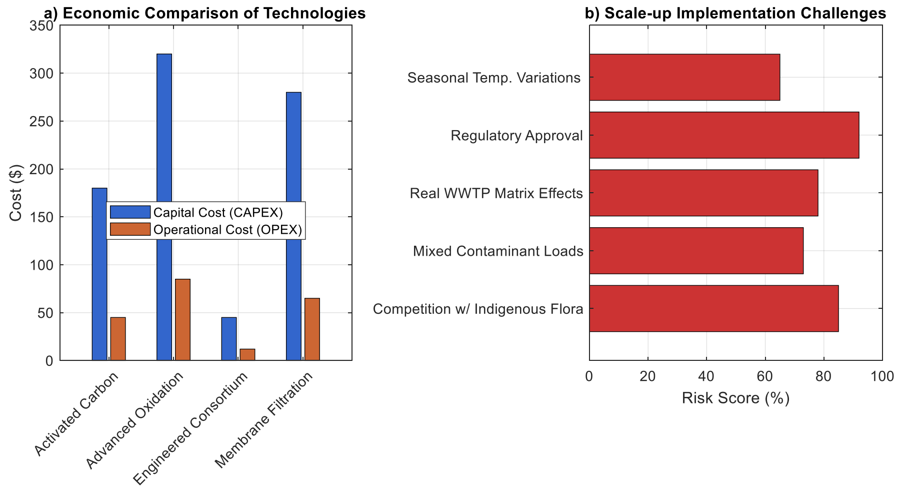

Figure 5: Results Commentary

Results of the batch degradation experiments can be summarized in Table 2 in terms of parameters of kinetic data. These values offer the basic foundation of reactor design and optimization of the process, which means that all of the desired compounds could be successfully degraded within operationally available periods under the reported optimal conditions.

Table 2: Summary of Kinetic Parameters for Antidepressant Degradation by the Engineered Consortium

Compound	Rate Constant, k (h^{-1})	Half-life, t½ (h)	Removal at 48 h (%)	Optimal pH	Optimal Temp (°C)
Sertraline	0.0450	15.4	88.5	6.5	30
Citalopram	0.0380	18.2	83.9	6.5	30
Fluoxetine	0.0420	16.5	86.7	6.5	30

The economic analysis provided in Table 3 proves the competitive nature of the microbial consortium approach and especially in the sector of operation expenditure in which it presents an 86% decrease in operation cost as applied in advanced oxidation. Footprint requirement (1.2 m2/m3/d) is also a mediocre indicator of the technologies compared based on the efficiency of the space and biological process need.

Table 3: Comparative Economic Analysis of Remediation Technologies

Technology	CAPEX ($/m³)	OPEX ($/1000 m³)	Footprint (m²/m³/d)	Key Limitation
Engineered Consortium	45	12	1.2	Regulatory approval (92% risk)

Advanced Oxidation	320	85	0.8	High energy consumption, toxic by-products
Activated Carbon	180	45	1.5	Non-destructive, waste generation
Membrane Filtration	280	65	0.7	Membrane fouling, high maintenance

Although the engineered consortium has shown encouraging effectiveness in carefully controlled laboratory experiments, a number of very important limitations and uncertainties should be mitigated before the practice can be implemented in real-life. The major problem is that there is the transition in the scale-up between specific laboratory microcosms to heterogeneous full-scale wastewater treatment systems. The challenges in engineering that are of interest are designing reactors to sustain the optimal conditions (pH 6.5, 30°C) and adequate mass transfer and biomass retention of the consortium which might not be in line with the current infrastructure. The competition with the native microbial flora in non-sterile sewage is a serious biological uncertainty. Even though data collected on qPCR show that the inoculum remains at 86.0 percent persistence during 30 days in a simulated matrix, actual wastewater harbors complicated and established communities and dynamic nutrient profiles that can either outcompete or inhibit the specialized consortium. The environmental and long-term sustainability of the new consortium is not known.

The regulatory and safety hurdle poses a significant challenge especially when genetic modification has been used to optimize the degradative pathways. Even bioremediation release of engineered microorganisms is subject to tight global biosafety regulations (e.g. EU Directive 2001/18/EC). The greatest challenge encountered is the risk score in regulatory approval with 92. The risk assessment of the horizontal gene transfer and the possible ecological side effects is obligatory.

Economic forecasts (CAPEX: $45/m3, OPEX: $12/1000 m3) are calculated on a utopian basis. The actual cost can be higher because of the costs of monitoring, process control system and the necessity to pre treat or post-treat the system. Economic analysis fails to consider the possible liability or insurance expenses on the implementation of a new bioaugmentation technology. Lastly, the transformational products of this research are not entirely discussed. Even though, complete mineralization is rated at 42.1, the nature and toxicity of intermediate metabolites are not defined. It has the risk of generating bioactive or persistent transformation products which might be as worrying or more so than the parent antidepressants. Thus, such restrictions highlight the essence of the strong necessity of pilot-scale testing in the real wastewater treatment setting. The integrated techno-economic and life-cycle assessments, long-term ecotoxicological research, and development of effective containment or control measures to reduce the risk of the future deployment of the field should be prioritized in work.

4. Conclusion and Future Perspectives

Finally, this research paper has managed to illustrate the evidence-of-concept of the microbial ecosystem engineering as an effective approach in addressing the pharmaceutical pollutants. A stable, multi-functional bacterial consortium is created and confirmed with the ability to efficaciously degrade, be able to operate effectively, and hold economic potential. Nevertheless, there are considerable obstacles to the transfer of laboratory simulation to the actual issue, among them the competition within the real wastewater matrices, the regulatory control, as well as the necessity to describe the products of transformation. It is thus adviced that the current future research should target on controlled pilot scale experiments in the real treatment plant scenarios to confirm the performance under realistic conditions. At the same time, the ecotoxicological evaluation of the degradation intermediates and life-cycle analyses should be performed thoroughly to safeguard the environment and avoid financial losses. It is suggested that the combination of systems biology tools, including metatranscriptomics and metabolomics, can be used to explain real-time consortia interactions and regulatory networks. Lastly, the idea of biofilm-based immobilization on sustainable carriers is proposed in order to improve the retention of the biomass and the stability of the processes, which will lead to the practical use of this engineered bioremediation platform.

5. References

1. Nadda, A.K., Banerjee, P. and Sharma, S. eds., 2024. *Microbes and Enzymes for Water Treatment and Remediation*. CRC Press.
2. Behera, S.S., Nivedita, S., Giri, S., Parwez, Z., Behera, P.K., Pradhan, S., Mohapatra, M., Mishra, A. and Ray, L., 2025. Microbial-Based Systems for Emerging Pollutant Removal from Sewage Waste: A Comprehensive Overview. *Biotechnological Removal of Emerging Pollutants from Wastewater Systems*, pp.245-283.
3. Bhatia, N., Kumari, A. and Sharma, R., 2025. Detoxification and Biodegradation of Pharmaceutics by Common Microorganisms. In *Biomedical Waste Management* (pp. 207-238). Apple Academic Press.
4. Anani, O.A., Adama, K.K. and Anani, A.G., 2024. Bacteria and Algae Consortia in Aquatic Ecosystem and the Effects of Personal Care

Products on Their Ecological Role. *Emergent Pollutants in Freshwater Plankton Communities*, pp.94-105.

5. Qattan, S.Y., 2025. Harnessing bacterial consortia for effective bioremediation: targeted removal of heavy metals, hydrocarbons, and persistent pollutants. *Environmental Sciences Europe*, *37*(1), p.85.
6. Senapati, T., Mondal, N.S. and Modak, B.K., 2025. Bioremediation of Pharmaceutically Active Compounds (PhACs): Strategies, Mechanisms, and Future Prospects. In *Biotechnological Removal of Emerging Pollutants from Wastewater Systems* (pp. 193-221). Singapore: Springer Nature Singapore.
7. Senapati, T., Mondal, N.S. and Modak, B.K., 2025. Mechanisms, and Future Prospects. *Biotechnological Removal of Emerging Pollutants from Wastewater Systems*, p.193.
8. PAIU, M., FAVIER, L. and GAVRILESCU, M., 2024. Emerging pollutants in the environment. II. Risks and mitigation technologies for sustainable environmental management. *Annals of the Academy of Romanian Scientists. Series on Physics and Chemistry*, *9*, pp.74-138.
9. Shah, M.P. ed., 2024. *Emerging Innovative Trends in the Application of Biological Processes for Industrial Wastewater Treatment*. Elsevier.
10. Van Heerden, A.D.F., 2023. *Microbial degradation of two halogenated pharmaceuticals for the recovery of natural aquatic environments* (Master's thesis, Universidade do Porto (Portugal)).
11. Tyumina, E., Subbotina, M., Polygalov, M., Tyan, S. and Ivshina, I., 2023. Ketoprofen as an emerging contaminant: occurrence, ecotoxicity and (bio) removal. *Frontiers in Microbiology*, *14*, p.1200108.
12. Low, M.L., Karim, J., Abu Tahrim, N., Tan, M.Y., Lim, K.S., Yeap, S.P., Mijan, N.A. and Ramalingam, M., 2024. Advancing Sustainable Water Quality Monitoring and Remediation in Malaysia: Innovative Analytical Solutions for Detecting and Removing Emerging Contaminants. *ACS ES&T Water*, *4*(11), pp.4758-4773.
13. Kumari, P., Sinha, S., Raj, D., Kumar, P. and Gupta, U., 2025. The potential of fungi in the bioremediation of xenobiotics: a mycological approach to water treatment. *Toxicological & Environmental Chemistry*, *107*(6), pp.1208-1245.
14. de Oliveira, B.F.R., Carr, C.M., Dobson, A.D. and Laport, M.S., 2020. Harnessing the sponge microbiome for industrial biocatalysts. *Applied Microbiology and Biotechnology*, *104*(19), pp.8131-8154.
15. de Oliveira, B.F.R., Carr, C.M., Dobson, A.D. and Laport, M.S., 2020. Harnessing the sponge microbiome for industrial biocatalysts. *Applied Microbiology and Biotechnology*, *104*(19), pp.8131-8154.

16. Dutta, P., Chakraborty, A., Amrit, R., Dey, P., Buragohain, T. and Osborne, W.J., 2025. Biotic remedies for Antibiotic pollution: A Review on Bioremediation Strategies. *Water, Air, & Soil Pollution*, *236*(7), p.440.
17. Pisciotta, J.M., Blessing, S. and Zaybak, Z., 2025. Wastewater Composition and Treatment Using Conventional and Bioelectrochemical Systems. In *Biotechnology for Environmental Sustainability* (pp. 507-559). Singapore: Springer Nature Singapore.
18. Reid, G., Allen-Vercoe, E., Al, K., Burton, J.P., Daisley, B., Dixon, B., Mousavi, H., Solberg, S.O., Peixoto, R.S., Silverman, M. and Skokovic-Sunjic, D., 2025. Beneficial microbes for One Health in Canada: a review of evidence and a policy proposal. *FACETS*, *10*, pp.1-32.
19. Fyfe, M.H., 2022. *Contaminants of Emerging Concern Treatment by Microalgae: The Status and Future of Phycoremediation* (Master's thesis, Queen's University (Canada)).
20. RAJ, Y., 2024. *Sculpturing Hypericum perforatum L. Rhizosphere for Enhanced Biomass and Secondary Metabolite Production under the Western Himalaya* (Doctoral dissertation, CSIR-Institute of Himalayan Bioresource Technology).
21. Salih, B.M., Nadweh, S., Abdulbaqi, A.S., Pasila, F., Essa, R.O. and Radhi, A.D., 2025. Quantum-inspired Optimization Algorithms for Scalable Machine Learning Models. *International Journal of Intelligent Engineering & Systems*, *18*(10).
22. Abdtawfeeq, T.H., Nadweh, S., Qudr, L.A.Z., Tawfeq, J.F., Radhi, A.D., Sekhar, R., Shah, P. and Gheni, H.M., 2025. Harnessing Neutrosophic Numerical Measures for Unbiased Quantitative Analysis of Oxidative Stress Biomarkers. *International Journal of Intelligent Engineering & Systems*, *18*(8).
23. Abdtawfeeq, T.H., Nadweh, S., Qudr, L.A.Z., Gheni, H.M., Radhi, A.D., Sekhar, R. and Shah, P., 2025. Optimizing Analytical Thresholds in Serum Proteomics Using Neutrosophic Logic Systems. *International Journal of Intelligent Engineering & Systems*, *18*(7).
24. Erhunmwunse, N.O., Pajiah, T.J. and Ogwu, M.C., 2024. Microplastics as water pollutants and sustainable management strategies. In *Water Crises and Sustainable Management in the Global South* (pp. 253-278). Singapore: Springer Nature Singapore.
25. MWANZA, S.S., 2024. *Harnessing the nutraceutical properties, Microbial composition of scarabaeoid beetle Larvae and antibacterial compounds of its Endozoic fungus (aspergillus welwitschia)* (Doctoral dissertation, Sylviah Syombua Mwanza).

26. Prasanth, T., Reddy, K.P. and Velayutham, R., 2025. The Next Frontier in Microbiome-Based Therapeutics: Advanced Clinical Applications. In *Microbiota Profiling for Precision Medicine: Biomarker-Targeted Drug Delivery Strategies* (pp. 385-408). Singapore: Springer Nature Singapore.