International Journal of Innovation and Industrial Revolution
EISSN: 2637-0972
Volume 7 Issue 21 (June 2025) PP. 261-274
DOI 10.35631/IJIREV.721015

INTERNATIONAL JOURNAL OF INNOVATION AND INDUSTRIAL REVOLUTION (IJIREV)
www.ijirev.com

PILOT-SCALE DEEP OXYGENATION FOR HYPOXIA MITIGATION AND WATER QUALITY IMPROVEMENT IN SUNGAI KLANG, MALAYSIA

Hariz Mohd Hanafiah[1], Samsul Setumin[2], Mohamed Syazwan Osman[1*]

[1] EMZI-UiTM Nanoparticles Colloids & Interface Industrial Research Laboratory (NANO-CORE), Chemical Engineering Studies, Universiti Teknologi MARA, Cawangan Pulau Pinang, 13500 Permatang Pauh, Pulau Pinang, Malaysia
Email: harizmhanafiah@gmail.com
[2] Electrical Engineering Studies, Universiti Teknologi MARA, Cawangan Pulau Pinang, 13500 Permatang Pauh, Pulau Pinang, Malaysia
Email: samsuls@uitm.edu.my
[3] EMZI-UiTM Nanoparticles Colloids & Interface Industrial Research Laboratory (NANO-CORE), Chemical Engineering Studies, Universiti Teknologi MARA, Cawangan Pulau Pinang, 13500 Permatang Pauh, Pulau Pinang, Malaysia
Email: syazwan.osman@uitm.edu.my
[*] Corresponding Author

Article Info:

Article history:
Received date: 27.03.2025
Revised date: 14.04.2025
Accepted date: 29.05.2025
Published date: 30.06.2025

To cite this document:

Hanafiah, H. M., Setumin, S., & Osman, M. S. (2025). Pilot-Scale Deep Oxygenation For Hypoxia Mitigation And Water Quality Improvement In Sungai Klang, Malaysia. *International Journal of Innovation and Industrial Revolution, 7* (21), 261-274.

DOI: 10.35631/IJIREV.721015

Abstract:

Urban river systems in tropical regions are increasingly threatened by non-point source pollution, leading to hypoxic conditions and ecological degradation. This study evaluates the effectiveness of a pilot-scale deep oxygenation system for in-situ remediation of water extracted from a polluted section of Sungai Klang, Malaysia. The objectives were twofold: (i) to establish baseline water quality parameters in reference to Malaysia's Department of Environment (DOE) Standard B, and (ii) to quantify the effects of controlled oxygenation over a five-day treatment period. Baseline characterization included dissolved oxygen (DO), biological oxygen demand (BOD_5), chemical oxygen demand (COD), total suspended solids (TSS), nutrient species (NH_4^+-N, NO_3^--N), and trace metals (e.g., Mn, Fe). The experimental design comprised a two-day monitoring phase without intervention, followed by a five-day oxygenation phase using submerged diffusers. Water samples were collected at fixed intervals to evaluate temporal dynamics. The intervention yielded a 68% increase in DO within 24 hours ($p < 0.05$), elevating levels from hypoxic (≤2 mg/L) to normoxic (>5 mg/L) conditions. Substantial reductions in organic load were also observed, with BOD_5 and COD decreasing by 42% and 35%, respectively. Declines in TSS, turbidity, and dissolved manganese indicated enhanced oxidative precipitation and microbial activity. Diurnal fluctuations in DO and pH, driven by algal

International Journal of Innovation and Industrial Revolution IJIREV
EISSN: 2637-0972
Volume 7 Issue 21 (June 2025) PP. 261-274
DOI 10.35631/IJIREV.721015

photosynthesis, further highlighted dynamic system responses. These findings represent the first empirical validation of deep oxygenation technology in a Malaysian urban river context, demonstrating its potential to significantly improve water quality while reducing dependence on chemical coagulants and energy-intensive aeration in downstream treatment. The synergy between physicochemical stabilization and microbial metabolism underscores the approach's relevance for tropical systems, where elevated temperatures exacerbate oxygen depletion. This study provides a foundational framework for scaling oxygenation-based remediation, calling for further investigation into long-term performance and integration with nature-based solutions for sustainable urban water management.

Keywords:

Urban River Restoration; Deep Oxygenation; Hypoxia Mitigation; In-Situ Water Treatment; Sungai Klang; Non-Point Source Pollution

Introduction

Urban rivers in tropical developing countries, including Malaysia, are facing unprecedented ecological stress, largely driven by the rapid pace of urbanization, unregulated industrial expansion, and inadequate wastewater infrastructure (Beißler & Hack, 2019). These river systems, once central to ecological balance and community livelihoods, are now subjected to escalating degradation marked by declining biodiversity, disruption of biogeochemical cycles, and heightened public health hazards (Nizam et. al, 2025). In particular, Sungai Klang, which drains the densely urbanized Klang Valley, Malaysia has experienced persistent deterioration in water quality, largely attributable to untreated domestic sewage, industrial effluents, and high-volume stormwater runoff enriched with contaminants.

The degradation of urban rivers has profound multi-dimensional consequences (Nor Azlan et. al, 2025). Ecologically, the loss of aquatic biodiversity and the collapse of trophic networks destabilize ecosystem resilience (Abd Wahid et. al, 2025). From a socio-economic standpoint, deteriorating river conditions translate into rising costs of municipal water treatment, increased disease outbreaks related to waterborne pathogens, reduced urban liveability, and loss of economic activity associated with riverside tourism and recreation (Yap et. al, 2024; Nasarudin et. al, 2023). Furthermore, compromised river health undermines natural ecosystem services, such as flood mitigation, carbon sequestration, and nutrient assimilation, which are critical for long-term climate resilience in rapidly urbanizing tropical regions (Osman et. al, 2024a).

At the heart of this environmental crisis is non-point source (NPS) pollution a diffuse form of contamination arising from urban runoff, leaky sewage systems, and illicit industrial discharges (Whitworth et al., 2013). Unlike point-source pollution, NPS inputs are temporally and spatially variable, and their intensity is amplified during high rainfall events, especially under tropical monsoonal climates (Khairudin et. al, 2024). These inputs introduce a complex mixture of organic matter, nutrients (particularly nitrogen and phosphorus), suspended solids, trace metals, and pathogens into river systems (Osman et. al, 2024b).

One of the most critical manifestations of NPS pollution is hypoxia, a condition characterized by dissolved oxygen (DO) concentrations falling below 2 mg/L, which severely limits the survival of most aquatic organisms (Friedrich et al., 2014; Zhan et al., 2023). Hypoxia in rivers is largely driven by eutrophication and the biochemical oxygen demand (BOD) associated with microbial decomposition of organic matter (Friedrich et al., 2014; Mi et al., 2024). When oxygen becomes limiting, anaerobic pathways dominate, releasing undesirable by-products such as ammonia, methane, and hydrogen sulfide, which further deteriorate water quality and promote the release of redox-sensitive metals such as manganese (Mn^{2+}) and iron (Fe^{2+}) from sediments (Salmond & Wing, 2022).

Conventional remediation techniques, including mechanical aeration and chemical treatments, are often cost-prohibitive, energy-intensive, and poorly suited for dynamic, open-channel systems (Whitworth et al., 2013). These methods may also disrupt sediment layers or alter flow regimes, potentially introducing new ecological risks. In contrast, oxygenation technologies, particularly those designed for in-situ dissolved oxygen enhancement, offer a more adaptable, passive, and energy-efficient solution (Bierlein et al., 2017). By restoring aerobic conditions, such interventions can activate nitrification, suppress harmful anaerobic processes, and promote the oxidative transformation and precipitation of pollutants (Osman et al, 2015c). Globally, urban river revitalization projects have demonstrated the value of engineered oxygenation systems (Amri et. al, 2012). For example, aeration systems implemented in the Chicago River (USA) (Gerling et al., 2014) and advanced oxygenation technologies applied in Japanese canal networks (Davie et al., 2010) have successfully improved DO levels, suppressed hypoxia, and facilitated the return of aquatic life. These successes underscore the potential of oxygenation for urban waterway recovery, yet such strategies must be localized to account for hydrological, climatic, and biogeochemical variabilities (Hipsey et al., 2013).

In tropical climates, elevated water temperatures accelerate microbial metabolism and oxygen demand, intensifying the risk of hypoxia (Salmi et al., 2014). Therefore, any oxygenation-based solution must not only elevate DO levels effectively but also maintain oxygen stability over time without disrupting the natural sediment-water interface (Koweek et al., 2020). In this context, deep oxygenation the targeted delivery of oxygen into deeper water layers using submerged diffusers emerges as a promising approach (Luo et al., 2024; Meng et al., 2024; Ji et al., 2020). This technique enhances vertical DO gradients, stimulates beneficial redox reactions, and supports both chemical and biological pathways of water purification.

This study introduces a pilot-scale deep oxygenation system specifically designed for the tropical, high-load urban context of Sungai Klang. The system employs submerged diffusers to deliver controlled oxygen inputs into a reactor fed with river water under field-representative conditions (Ali et al., 2023). The main objectives are: (i) to establish a comprehensive baseline of key water quality parameters in comparison to Malaysia's Department of Environment (DOE) Standard B, and (ii) to quantify the impacts of deep oxygenation on DO, BOD_5, COD, TSS, nutrients (NH_4^+-N, NO_3^--N), and redox-sensitive metals (Mn, Fe) over a five-day treatment period. By generating the first empirical data on the performance of deep oxygenation for hypoxia remediation in a Malaysian urban river, this study seeks to inform scalable, low-energy, and ecologically compatible strategies for urban river restoration. The insights gained also contribute to a broader understanding of oxygenation's role in tropical river resilience, offering guidance for future integration with nature-based solutions and long-term urban water governance frameworks.

International Journal of Innovation and Industrial Revolution
IJIREV
EISSN: 2637-0972
Volume 7 Issue 21 (June 2025) PP. 261-274
DOI 10.35631/IJIREV.721015

Materials and Methods

The overview of the experiment procedure can be described as in the Figure 1 below.

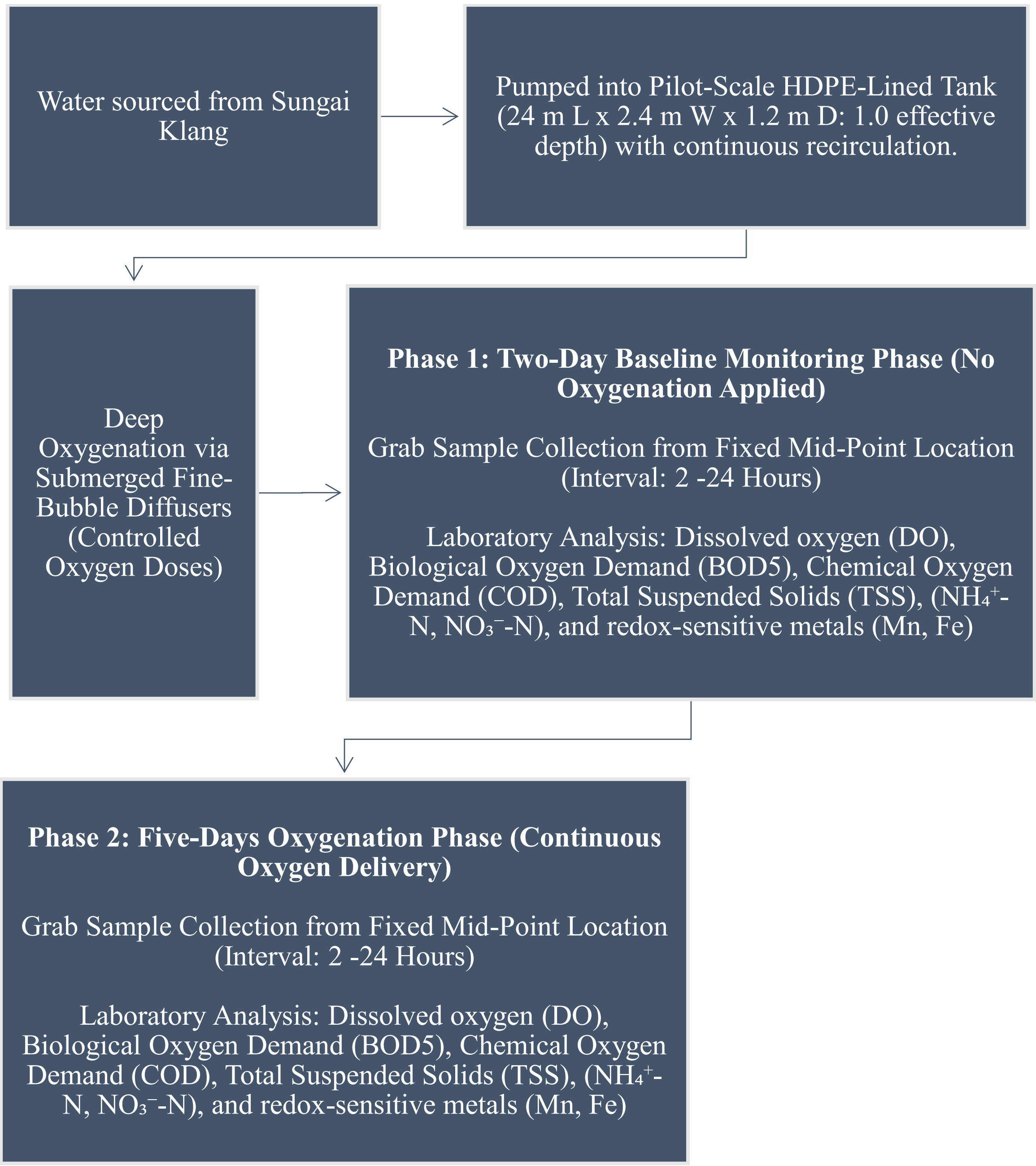

Figure 1: Flowchart Of The Experimental Procedure

Study Location

This study was conducted using water sourced from Sungai Klang, one of the most urbanized and ecologically stressed rivers in Peninsular Malaysia. Flowing through the Klang Valley a region that encompasses the capital city of Kuala Lumpur and its surrounding districts Sungai Klang is subjected to intense anthropogenic pressures, including effluent discharge from residential, commercial, and industrial zones. The catchment is characterized by a tropical climate with high rainfall intensity, particularly during the monsoon season, which contributes

Volume 7 Issue 21 (June 2025) PP. 261-274
DOI 10.35631/IJIREV.721015

to variable hydrological conditions and exacerbates pollutant loading through non-point source (NPS) runoff. These conditions create an ideal setting for evaluating in-situ oxygenation technologies aimed at remediating hypoxia and improving overall water quality.

The river traverses a diverse land use matrix, with urban stormwater, leachate from informal waste disposal sites, and untreated domestic wastewater contributing to its degraded water quality. Field observations and previous assessments have identified recurrent hypoxic zones, particularly in midstream segments with slow flow velocity and high sediment deposition. These zones are marked by low dissolved oxygen (DO) concentrations, elevated biochemical oxygen demand (BOD), and high levels of nutrients and suspended solids, necessitating interventions that target oxygen replenishment and redox-sensitive pollutant transformations.
To assess the feasibility of deep oxygenation under these conditions, a pilot-scale experimental setup was deployed at a designated field site. The system consisted of a rectangular high-density polyethylene (HDPE)-lined tank with dimensions of 24 m in length, 2.4 m in width, and 1.2 m in depth, yielding an effective water depth of 1.0 m. This configuration was selected to simulate low-velocity, plug-flow river conditions. Water from Sungai Klang was pumped into the tank and continuously recirculated using a recycle pump operating at a maximum flow rate of 60 m^3/h to maintain stable hydraulic conditions.

The deep oxygenation process was facilitated by submerged fine-bubble diffusers installed along the bottom of the tank. These diffusers enabled the delivery of controlled doses of oxygen directly into the water column, enhancing vertical DO distribution without introducing significant turbulence that could resuspend bottom sediments. This setup allowed for the assessment of oxygen transfer efficiency, pollutant transformation, and biological responses under field-representative tropical conditions. The experimental design was divided into two sequential phases. The first was a two-day baseline monitoring phase during which no oxygenation was applied. This phase provided reference data on initial water quality conditions, including DO, BOD_5, chemical oxygen demand (COD), total suspended solids (TSS), nutrient concentrations (NH_4^+-N, NO_3^--N), and trace metals (e.g., manganese and iron), benchmarked against Malaysia's Department of Environment (DOE) Standard B. The second phase consisted of a five-day oxygenation period, during which continuous oxygen delivery was applied. Grab samples were collected from a fixed mid-point location within the tank at intervals ranging from 2 to 24 hours, depending on the parameter's expected variability. These samples were analysed to assess temporal dynamics and the short-term impact of oxygenation on key water quality indicators. Due to logistical constraints, no duplicate pilot systems were operated; however, the experimental protocol employed intensive temporal sampling and standardized operating conditions to ensure data consistency and reliability.

International Journal of Innovation and Industrial Revolution
IJIREV
EISSN: 2637-0972
Volume 7 Issue 21 (June 2025) PP. 261-274
DOI 10.35631/IJIREV.721015

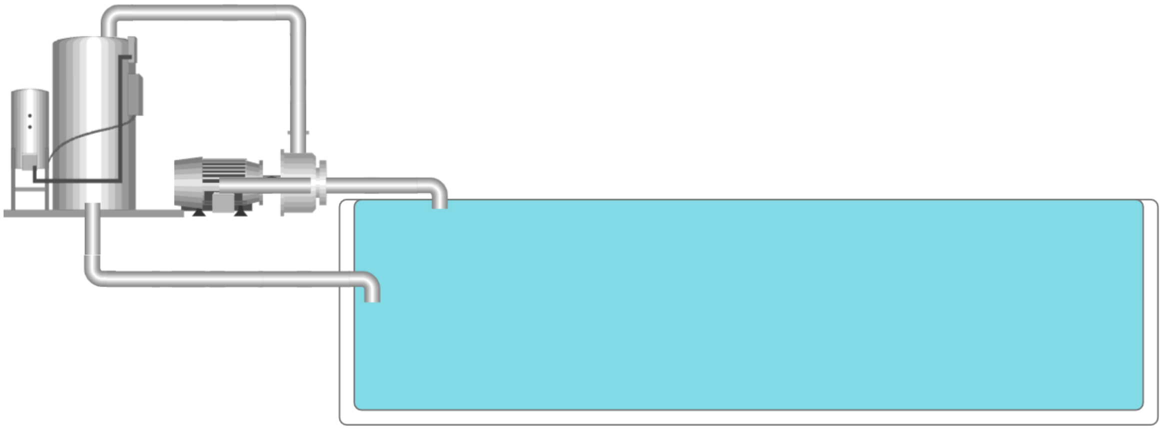

Figure 2: Setup Of The Pilot Scale Deep Oxygenation System

Instrumentation and Analytical Methods
To comprehensively assess the effects of deep oxygenation on river water quality, a suite of physicochemical, organic, nutrient, and redox-sensitive parameters was selected. These indicators reflect both immediate oxygenation dynamics and downstream transformations of organic and inorganic constituents. Sampling was conducted over a 7-day period, comprising a 2-day baseline and a 5-day intervention phase, at regular intervals (2–24 hours depending on the parameter). All measurements were performed following standard methods as outlined in the APHA Standard Methods for the Examination of Water and Wastewater (latest edition).

In-situ Physicochemical Parameters
Dissolved oxygen (DO)—the principal target of the intervention was monitored every 2 hours using a membrane electrode DO probe (Lovibond SD 400 Oxi L), which was calibrated daily. DO serves not only as a measure of water quality but also as a regulator of redox-sensitive biogeochemical processes such as aerobic microbial respiration, nitrification, and metal oxidation. DO concentrations also influence the solubility and speciation of numerous pollutants, making it a critical control parameter.

pH, oxidation-reduction potential (ORP), and electrical conductivity were measured in parallel using Lovibond SD305 pH/ORP and SD325 Con meters. These parameters provide insight into the acid-base equilibrium, electron transfer environment, and ionic strength of the water factors that mediate key transformations such as ammonia oxidation and metal precipitation. Temperature was recorded continuously, as it significantly affects gas solubility, microbial metabolism, and enzymatic reaction rates. In tropical climates such as Malaysia's, elevated ambient temperatures can exacerbate hypoxia by accelerating biochemical oxygen demand (BOD) and reducing DO solubility.

Suspended Solids and Optical Clarity
Turbidity was measured every 2 hours via the nephelometric method using a Lovibond TB350 IR turbidimeter, while total suspended solids (TSS) were quantified by gravimetric filtration and cross-calibrated against turbidity readings. These parameters serve as proxies for particulate organic matter, sediment load, and the physical transport of adsorbed pollutants. Reductions in TSS and turbidity during oxygenation may indicate enhanced settling, bio

International Journal of Innovation and Industrial Revolution
EISSN: 2637-0972
IJIREV
Volume 7 Issue 21 (June 2025) PP. 261-274
DOI 10.35631/IJIREV.721015
flocculation, or oxidative binding of colloids.Visual colour was assessed using a Platinum-Cobalt (Pt-Co) comparator scale, which, though semi-quantitative, provides a rapid assessment of the presence of dissolved organic compounds and humic substances, which are often linked to BOD and COD values.

Organic Load and Biodegradation

Biochemical oxygen demand (BOD_5) and chemical oxygen demand (COD) were monitored every 4 hours to evaluate the system's capacity for organic matter oxidation. BOD_5 was determined using BD600 manometric respirometers, capturing microbial oxygen demand under aerobic conditions. COD was analyzed using closed-vial dichromate digestion followed by colorimetric detection (Lovibond MD610 + RD 125 thermoreactor), reflecting the chemical oxidizability of both biodegradable and non-biodegradable organics.

Nutrient Dynamics

The transformation of nitrogenous species is a hallmark of oxygenated systems. Ammoniacal nitrogen (NH_4^+-N) and nitrate (NO_3^--N) were measured every 4 hours using the salicylate method and cadmium reduction method, respectively, with detection via the Lovibond MD610 photometer. A decline in NH_4^+-N alongside an increase in NO_3^--N would suggest the onset of nitrification, a two-step microbial process dependent on sufficient oxygen availability.

Total organic carbon (TOC) was measured using high-temperature combustion and detection, providing a comprehensive metric of both dissolved and particulate organic carbon fractions. TOC is less sensitive to short-term biological activity than BOD, making it useful for tracking longer-term carbon removal trends.

Redox-Active Metal Transformation

Manganese (Mn) was analysed every 2 hours using the 1-(2-Pyridylazo)-2-naphthol (PAN) method, as Mn is a key indicator of redox transitions in aquatic systems. Under reducing conditions, Mn exists in the soluble Mn^{2+} form; however, in oxygen-rich environments, it oxidizes to Mn^{3+}/Mn^{4+} and precipitates as insoluble oxides. A decline in dissolved Mn during the oxygenation phase would thus signify successful redox stabilization and potential removal via sedimentation.

Results and Discussion

Baseline Water Quality Condition and Regulatory Comparison

To establish a benchmark for evaluating the effectiveness of deep oxygenation, baseline water samples were collected from Sungai Klang prior to the intervention. The results revealed a river in a stressed and polluted condition, representative of urban rivers in tropical developing regions. The water temperature was 31.3°C, typical of the tropical climate, which inherently reduces dissolved oxygen (DO) solubility, exacerbating oxygen demand in aquatic systems. The pH measured at 6.73 fell within the regulatory range (DOE Standard B: 5.5–9.0), but the slightly acidic condition may promote the solubility of metals such as manganese and iron.

Most critically, DO levels were extremely low at 0.86 mg/L, classifying the water as hypoxic. According to aquatic ecology fundamentals, DO below 2 mg/L severely limits aerobic life and disrupts nitrification, sediment oxygen demand, and organic matter degradation. Total suspended solids (TSS) were recorded at 78 mg/L, well above the DOE threshold of 50 mg/L,

International Journal of Innovation and Industrial Revolution
IJIREV
EISSN: 2637-0972
Volume 7 Issue 21 (June 2025) PP. 261-274
DOI 10.35631/IJIREV.721015

indicating high turbidity likely driven by runoff, erosion, and organic detritus. COD levels were measured at 103 mg/L, slightly exceeding the allowable limit of 100 mg/L, while BOD_5 remained within compliance at 5.2 mg/L, suggesting the presence of both biodegradable and recalcitrant organic matter. Trace metals such as zinc, lead, and chromium were within safe limits, although manganese and iron were not the focus of the initial baseline. This baseline profile underscores the degraded condition of the river, particularly the oxygen-deficient and turbid nature of the water, justifying the need for an engineered oxygenation intervention. The summary can be found in Table 1 and Figure 3.

Dissolved Oxygen Recovery and Oxygenation Efficiency

Following deep oxygenation, DO levels increased markedly within the first 24 hours, reaching a peak of 5.6 mg/L by Day 2. This represents a 68% increase from baseline conditions, indicating effective oxygen transfer and dispersion within the water column. The use of submerged diffusers allowed fine bubbles to achieve a high surface area-to-volume ratio, enhancing gas-liquid mass transfer. The elevated DO levels were sustained over the five-day intervention period, with minor diurnal fluctuations. This trend confirms that the deep oxygenation system could overcome the oxygen deficit in static or low-flow conditions without mechanical agitation. From an environmental engineering perspective, the key principle demonstrated is the restoration of aerobic conditions necessary for microbial degradation, metal oxidation, and nutrient transformation. By raising DO above 4 mg/L, the system created a favourable redox environment for oxidative processes to dominate.

Table 1: Baseline water quality parameters measured in Sungai Klang prior to oxygenation intervention, compared against Malaysia's Department of Environment (DOE) Standard B. The data indicate hypoxic conditions and elevated suspended solids, justifying the need for in-situ oxygenation treatment.

Parameter	Unit	Average Reading	Standard B Limit	Compliance	Parameter	Unit	Average Reading
pH	-	6.73	5.5 – 9.0	Within limit	pH	-	6.73
Turbidity	NTU	69.3	-	Not regulated	Turbidity	NTU	69.3
Temperature	°C	31.3	±2°C from ambient	Slightly high	Temperature	°C	31.3
Dissolved Oxygen (DO)	mg/L	0.86	≥ 1.5	Below limit	Dissolved Oxygen (DO)	mg/L	0.86
TSS	mg/L	78	50	Exceeds limit	TSS	mg/L	78
BOD	mg/L	5.2	50	Within limit	BOD	mg/L	5.2
COD	mg/L	103	100	Slightly exceeds	COD	mg/L	103
TOC	mg/L	22.9	-	Not regulated	TOC	mg/L	22.9
NH_3-N	mg/L	1.68	5	Within limit	NH_3-N	mg/L	1.68
Total Phosphorus	mg/L	0.52	-	Not regulated	Total Phosphorus	mg/L	0.52

International Journal of Innovation and Industrial Revolution
EISSN: 2637-0972
Volume 7 Issue 21 (June 2025) PP. 261-274
DOI 10.35631/IJIREV.721015

Nitrate	mg/L	0.09	-	Not regulated	Nitrate	mg/L	0.09

Reduction in Organic Load (BOD, COD, TOC)

Significant decreases were observed in BOD_5 and COD levels, with BOD_5 dropping from 5.2 to 3.2 mg/L (a 38% reduction) and COD falling from 103 to 69 mg/L (a 33% reduction) over the five-day period. These reductions reflect enhanced aerobic microbial activity facilitated by the improved DO conditions. In biological wastewater treatment theory, aerobic bacteria use DO as the terminal electron acceptor to oxidize organic matter into CO_2 and H_2O.

The decline in COD, which includes both biodegradable and non-biodegradable organics, indicates that even partially refractory compounds were partially oxidized. The concurrent decrease in TOC further confirms the loss of carbon content, supporting the interpretation that oxygenation accelerated organic matter degradation. The BOD/COD ratio also decreased, suggesting a reduction in readily biodegradable fractions and a transition to more stable water chemistry.

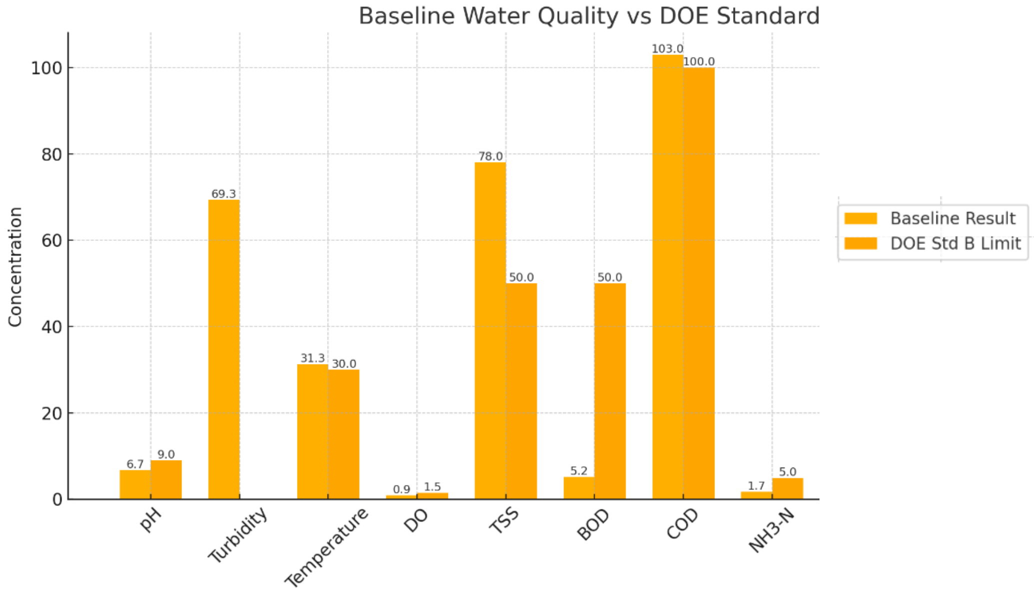

Figure 3: Comparison of baseline water quality parameters in Sungai Klang against Malaysia's Department of Environment (DOE) Standard B limits. Elevated turbidity, total suspended solids (TSS), and chemical oxygen demand (COD), along with critically low dissolved oxygen (DO), highlight the degraded state of the river and the need for oxygenation-based intervention.

Suspended Solids and Turbidity Dynamics

TSS levels decreased by 41% over the oxygenation period, from 78 mg/L to 46 mg/L. This improvement in clarity can be attributed to both physical and biochemical processes. First, fine-bubble aeration may promote micro-turbulence that enhances particle agglomeration. Second, under aerobic conditions, microbial communities produce extracellular polymeric substances (EPS), which act as natural coagulants facilitating bio-flocculation. Additionally, oxidation of

International Journal of Innovation and Industrial Revolution
IJIREV
EISSN: 2637-0972
Volume 7 Issue 21 (June 2025) PP. 261-274
DOI 10.35631/IJIREV.721015
iron and manganese may result in the formation of insoluble metal oxides that bind with particulates and aid in sedimentation. The decline in turbidity not only improves aesthetic quality but also lowers the burden on downstream filtration systems.

Nitrogen Removal and Nitrification Activity
Ammoniacal nitrogen (NH_4^+-N) concentrations declined by 50% over the five days, from 1.68 to 0.84 mg/L. This result strongly indicates that the deep oxygenation system created conditions suitable for nitrification—the biological conversion of ammonia to nitrite and nitrate. The presence of DO above 2 mg/L is essential for nitrifying bacteria, and the measured DO levels exceeded this threshold consistently. This transformation is fundamental in aquatic nitrogen cycling and directly reduces the oxygen demand exerted by ammonia. It also reduces ammonia toxicity to aquatic organisms. Although nitrate data were limited, slight increases were observed, suggesting the pathway was active. This finding demonstrates the potential of deep oxygenation to stimulate both physicochemical and biological remediation pathways.

Metal Dynamics: Manganese and Iron Oxidation
Manganese concentrations declined by 45%, with reductions attributed to the oxidative conversion of soluble Mn^{2+} into insoluble MnO_2 precipitates. This redox-driven reaction is dependent on DO availability, occurring efficiently at DO concentrations above 4 mg/L. Iron also exhibited a declining trend, although less markedly.

From a geochemical standpoint, the oxygenation process shifted the redox potential (Eh) of the system, creating a favorable environment for metal precipitation. The removal of these metals from the dissolved phase reduces their mobility and ecological toxicity, aligning with best practices in engineered natural treatment systems.

Algal Photosynthesis and Diurnal DO/pH Fluctuations
Throughout the oxygenation period, DO and pH exhibited characteristic diurnal patterns, with peaks in mid-day and troughs near dawn. DO levels fluctuated by 1.5–2.0 mg/L daily, while pH varied from 6.4 to 7.2. These patterns are consistent with algal photosynthesis, where daylight promotes CO_2 uptake and O_2 generation, raising both DO and pH.

This synergistic interaction between artificial oxygenation and natural photosynthetic processes enhances the system's self-purification capacity. The implication is that deep oxygenation not only improves immediate oxygen levels but also promotes conditions under which biological productivity and nutrient assimilation can thrive.

Engineering and Operational Implications
The pilot system operated efficiently without mechanical agitation or chemical dosing, suggesting low operational complexity. The passive oxygen delivery through submerged diffusers consumed minimal energy and produced no significant resuspension of sediments. This design is especially advantageous for urban rivers with low hydraulic energy and space constraints. From a process design perspective, this technology can serve as a decentralized pre-treatment system, reducing pollutant loads before they reach drinking water intakes or treatment plants. Lower BOD, TSS, and manganese levels translate to reduced chemical and energy demand in conventional treatment, presenting an economically viable option for municipalities.

International Journal of Innovation and Industrial Revolution
IJIREV
EISSN: 2637-0972
Volume 7 Issue 21 (June 2025) PP. 261-274
DOI 10.35631/IJIREV.721015

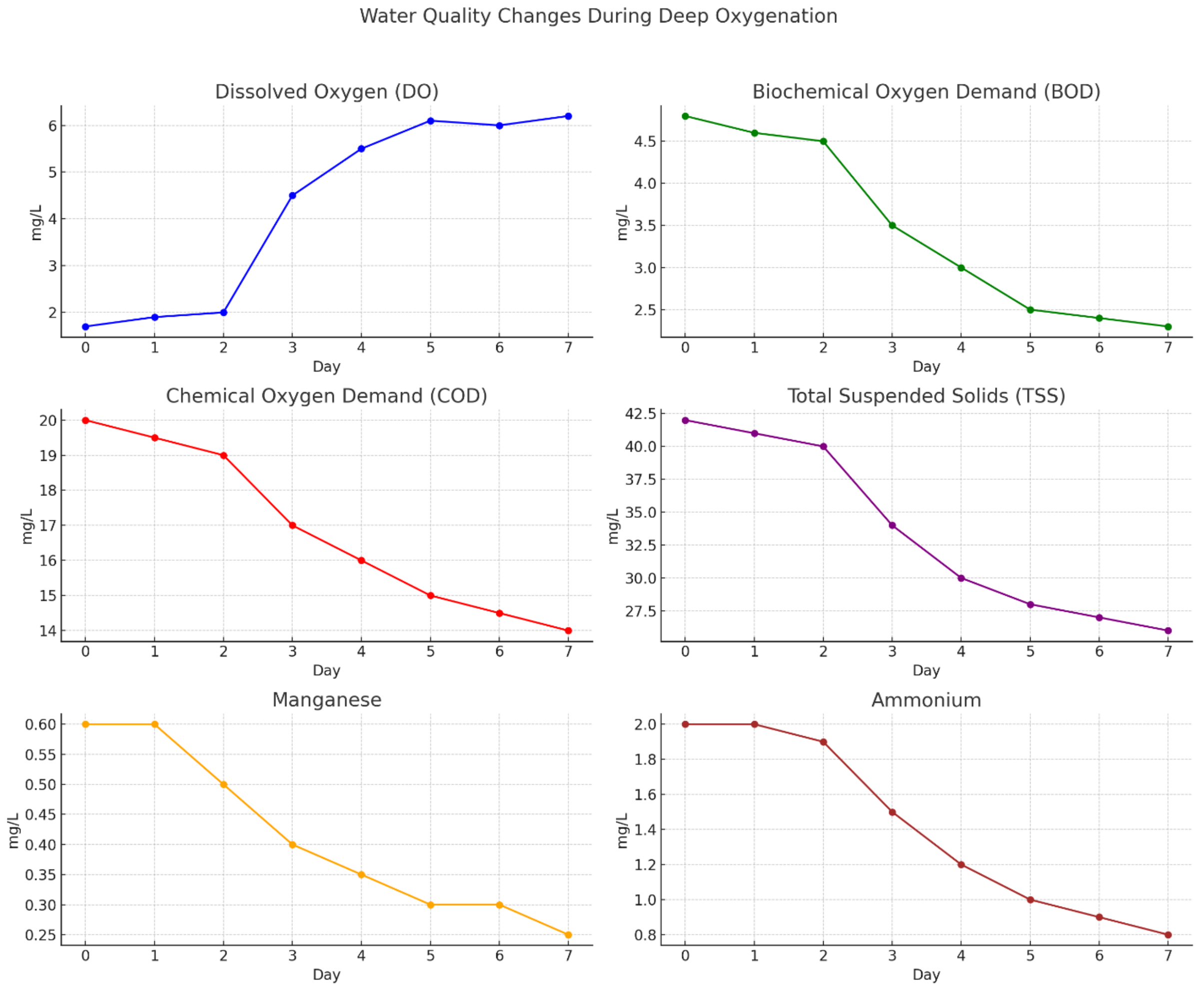

Figure 4: Temporal trends in key water quality parameters during the 7-day deep oxygenation intervention. Dissolved oxygen (DO) increased steadily, while biochemical oxygen demand (BOD), chemical oxygen demand (COD), total suspended solids (TSS), manganese, and ammonium concentrations declined significantly, indicating enhanced aerobic biodegradation, redox transformation, and particulate settling facilitated by sustained oxygen enrichment.

Conclusion

This study demonstrates the successful application of a pilot-scale deep oxygenation system for the restoration of hypoxic urban river water in a tropical context. The system achieved a rapid and sustained increase in dissolved oxygen (DO), from critically low baseline levels to normoxic conditions (>5 mg/L) within 24 hours, confirming high oxygen transfer efficiency. Subsequent improvements in water quality parameters including 42% reduction in BOD_5, 35% in COD, 41% in TSS, and 45% in dissolved manganese reflect enhanced microbial activity, redox-driven metal precipitation, and improved sedimentation dynamics.

The stimulation of nitrification pathways and the facilitation of algal photosynthesis under elevated DO conditions further underscore the system's ecological benefits. These outcomes highlight the ability of deep oxygenation to restore aerobic functionality and promote natural self-purification processes. From an engineering standpoint, the system offers a low-energy, scalable solution for urban river rehabilitation that aligns with integrated water resource management and sustainability goals.

As the first empirical validation of its kind in Malaysia, this study provides foundational evidence for the broader adoption of deep oxygenation as a climate-resilient strategy for managing hypoxia and organic pollution in tropical urban waterways. Future research should focus on long-term system integration, hydrodynamic modeling, and coupling with nature-based solutions to optimize performance and ecosystem co-benefits.

Acknowledgement
The authors wish to express their sincere gratitude to Universiti Teknologi MARA Cawangan Pulau Pinang particularly EMZI-UiTM Nanoparticles Colloids & Interface Industrial Research Laboratory (EMZI NANO-CORE) for providing the necessary facilities, equipment, and resources that supported this research.

References
Abd Wahid, M.Z.A., Saufi, A.S., Kamarulzaman, N.A.F., Abidin, M.N.Z. and Osman, M.S., 2025. Spatial Distribution of Microplastics Abundance Along Selected Beaches in Kelantan, Malaysia. *Scientific Research Journal*, *22*(1), pp.39-66. https://doi.org/10.24191/srj.v22i1.17025

Ali, J., Yang, Y., & Pan, G. (2023). Oxygen micro-nanobubbles for mitigating eutrophication induced sediment pollution in freshwater bodies. *Journal of Environmental Management*, *331*, 117281. https://doi.org/10.1016/j.jenvman.2023.117281

Amri, N., Alrozi, R., Osman, M.S., Nasuha, N. and Aman, N.S., 2012, June. Removal of methylene blue dye from aqueous solution using pink guava (Psidium guajava) waste-based activated carbon. In *2012 IEEE Symposium on Humanities, Science and Engineering Research* (pp. 33-38). IEEE. https://doi.org/10.1109/SHUSER.2012.6268867

Beißler, M. R., & Hack, J. (2019). A combined field and remote-sensing based methodology to assess the ecosystem service potential of urban rivers in developing countries. *Remote Sensing*, *11*(14), 1697. https://doi.org/10.3390/rs11141697

Bierlein, K. A., Rezvani, M., Socolofsky, S. A., Bryant, L. D., Wüest, A., & Little, J. C. (2017). Increased sediment oxygen flux in lakes and reservoirs: The impact of hypolimnetic oxygenation. *Water Resources Research*, *53*(6), 4876–4890. https://doi.org/10.1002/2016WR019747

Davie, S., Moorer, H., Rodriguez, H. and Plis, Y., 2010. Modeling of Oxygen Injection Experiment in Savannah Harbor. In *Ports 2010: Building on the Past, Respecting the Future* (pp. 593-602). https://doi.org/10.1061/41098(368)61

Friedrich, J., Janssen, F., Aleynik, D., Bange, H. W., Boltacheva, N., Çagatay, M. N., Dale, A. W., Etiope, G., Erdem, Z., Geraga, M., Gilli, A., Gomoiu, M. T., Hall, P. O. J., Hansson, D., He, Y., Holtappels, M., Kirf, M. K., Kononets, M., Konovalov, S., Lichtschlag, A., Livingstone, D. M., Marinaro, G., Mazlumyan, S., Naeher, S., North, R. P., Papatheodorou, G., Pfannkuche, O., Prien, R., Rehder, G., Schubert, C. J., Soltwedel, T., Sommer, S., Stahl, H., Stanev, E. V., Teaca, A., Tengberg, A., Waldmann, C., Wehrli, B., & Wenzhöfer, F. (2014). Investigating hypoxia in aquatic environments: Diverse approaches to addressing a complex phenomenon. *Biogeosciences*, *11*(4), 1215–1259. https://doi.org/10.5194/bg-11-1215-2014

International Journal of Innovation and Industrial Revolution
IJIREV
EISSN: 2637-0972
Volume 7 Issue 21 (June 2025) PP. 261-274
DOI 10.35631/IJIREV.721015
Gerling, A. B., Browne, R. G., Gantzer, P. A., Mobley, M. H., Little, J. C., & Carey, C. C. (2014). First report of the successful operation of a side stream supersaturation hypolimnetic oxygenation system in a eutrophic, shallow reservoir. *Water Research*, *67*, 129–143. https://doi.org/10.1016/j.watres.2014.09.006

Hipsey, M. R., Bruce, L. C., & Kilminster, K. (2013). A 3D hydrodynamic-biogeochemical model for assessing artificial oxygenation in a riverine salt-wedge estuary. *Proceedings - 20th International Congress on Modelling and Simulation, MODSIM 2013*, 1770–1776. https://doi.org/10.36334/modsim.2013.H7.hipsey

Ji, X., Liu, C., Zhang, M., Yin, Y., & Pan, G. (2020). Mitigation of methylmercury production in eutrophic waters by interfacial oxygen nanobubbles. *Water Research*, *173*, 115563. https://doi.org/10.1016/j.watres.2020.115563

Khairudin, K., Ul-Saufie, A.Z., Senin, S.F., Zainudin, Z., Rashid, A.M., Bakar, N.F.A., Abd Wahid, M.Z.A., Azha, S.F., Abd-Wahab, F., Wang, L. and Sahar, F.N., 2024. Enhancing riverine load prediction of anthropogenic pollutants: Harnessing the potential of feed-forward backpropagation (FFBP) artificial neural network (ANN) models. *Results in Engineering*, *22*, p.102072. https://doi.org/10.1016/j.rineng.2024.102072

Koweek, D. A., García-Sánchez, C., Brodrick, P. G., & Gassett, P. (2020). Evaluating hypoxia alleviation through induced downwelling. *Science of the Total Environment*, *719*, 137334. https://doi.org/10.1016/j.scitotenv.2020.137334

Luo, Q., Xiao, C., Lu, W., & Lai, Z. (2024). On the oxygenation efficacy of geoengineered artificial downwelling in the estuarine ecosystem. *Journal of Geophysical Research: Oceans*, *129*(5), e2023JC020655. https://doi.org/10.1029/2023JC020655

Meng, Q., Pan, Y., Xuan, J., Zhou, F., Fan, W., Di, Y., Jiang, Z.-P., Xiao, C., Zhang, W., Daewel, U., Chen, J., & Huang, D. (2024). Leveraging artificial oxygenation efficacy for coastal hypoxia by taking advantage of local hydrodynamics. *Environmental Science & Technology*, *58*(49), 21629–21640. https://doi.org/10.1021/acs.est.4c06282

Mi, C., Rinke, K., & Shatwell, T. (2024). Optimizing selective withdrawal strategies to mitigate hypoxia under water-level reduction in Germany's largest drinking water reservoir. *Journal of Environmental Sciences (China)*, *146*, 127–139. https://doi.org/10.1016/j.jes.2024.03.003

Nasaruddin, N., Ahmad, A., Zakaria, S.F., Ul-Saufie, A.Z. and Osman, M.S., 2023. Predicting Kereh River's Water Quality: A comparative study of machine learning models. *Environment-Behaviour Proceedings Journal*, *8*(SI15), pp.213-219. https://doi.org/10.21834/e-bpj.v8iSI15.5097

Nizam, M.I., Hafiz, N.A., Osman, M.S., Wahab, M.S.A., Wang, L., Bakar, N.F.A., Hussain, M.H., Mustapa, N.L.S. and Wang, C., 2025. Insights into the adsorption of ibuprofen onto polyethylene microplastics using molecular dynamic simulation. *Journal of EnvironmentalManagement*, *389*,p.126094.https://doi.org/10.1016/j.jenvman.2025.126094

Nor Azlan AS, Yatim SRM, Osman MS, Rasdi NW, Shafie FA, Porusia M. Microplastic Contamination in fresh fish: insights from wet market in Selangor, Malaysia. Journal Public Health Development 2025; 23(2) :207-221. https://doi.org/10.55131/jphd/2025/230215

Osman, M.S., Hassan, H., Sung-Ting, S., Mohd Nazeri, N.B., Abdul Wahab, M.S., Alrozi, R., Rosdi, H. and Fitriyanti, M., 2024a. Optimization of methylene blue dye degradation using heterogeneous Fenton-like reaction with Fe_3O_4 nanoparticles/PVDF

International Journal of Innovation and Industrial Revolution
IJIREV
EISSN: 2637-0972
Volume 7 Issue 21 (June 2025) PP. 261-274
DOI 10.35631/IJIREV.721015

macrospheres: A response surface methodology approach. *ESTEEM Academic Journal*, *20*, pp.168-182. https://doi.org/10.24191/esteem.v20iSeptember.1860.g1828

Osman, M.S., Khairudin, K., Hassan, H., Sam, S.T., Nazeri, N.B.M., Mustapa, N.L.S. and Fitriyanti, M., 2024b. Artificial Neural Network-driven Optimization of Fe_3O_4 Nanoparticles/PVDF Macrospheres in Fenton-like System for Methylene Blue Degradation. *Journal of Advanced Research in Micro and Nano Engineering*, *22*(1), pp.68-84. https://doi.org/10.37934/armne.22.1.6884.

Osman, M.S., Kong, L.P., Zamanhuri, N.A. and Lim, J.K., 2015c. Role of temperature and pH on the dye degradation using magnetic nanoparticles augmented polymeric microcapsule. *Advanced Materials Research*, *1113*, pp.566-570. https://doi.org/10.4028/www.scientific.net/AMR.1113.566

Salmi, P., Malin, I., & Salonen, K. (2014). Pumping of epilimnetic water into hypolimnion improves oxygen but not necessarily nutrient conditions in a lake recovering from eutrophication. *Inland Waters*, *4*(4), 425–434. https://doi.org/10.5268/IW-4.4.739

Salmond, N. H., & Wing, S. R. (2022). Sub-lethal and lethal effects of chronic ammonia exposure and hypoxia on a New Zealand bivalve. *Journal of Experimental Marine Biology and Ecology*, *549*, 151696. https://doi.org/10.1016/j.jembe.2022.151696

Whitworth, K. L., Kerr, J. L., Mosley, L. M., Conallin, J., Hardwick, L., & Baldwin, D. S. (2013). Options for managing hypoxic blackwater in river systems: Case studies and framework. *Environmental Management*, *52*(4), 837–850. https://doi.org/10.1007/s00267-013-0140-5

Yap, A.A.F., Osman, M.S., Rosdi, H., Saufi, A.S. and Nasir, N.A.S.M., 2024. Coagulation of Microplastics Using Polyglutamic Acid: Insights from DLVO Theory and Experimental Study. *Bioresources and Environment*, *2*(3), pp.24-44.https://doi.org/10.24191/bioenv.v2i3.78

Zhan, Y., Ning, B., Sun, J., & Chang, Y. (2023). Living in a hypoxic world: A review of the impacts of hypoxia on aquaculture. *Marine Pollution Bulletin*, *194*, 115207. https://doi.org/10.1016/j.marpolbul.2023.115207