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Enhancing urban catchment management using integrated CDS technology and nature-based solutions for stormwater quality improvement

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Abstract: Urban catchments are increasingly facing water-related challenges driven by rapid development and climate change. Conventional stormwater management is often inadequate, particularly in removing gross pollutants and sediments. This study explores an integrated approach combining continuous deflective separation (CDS) technology with nature-based solutions (NbS), including biochar, green zeolite, and floating wetlands planted with Vetiver grass, implemented at a commercial urban site in Malaysia. An on-site Internet of Things (IoT)-based monitoring system tracks water quality parameters: pH, turbidity, electrical conductivity (*EC*), dissolved oxygen (DO), total dissolved solids (TDS), and temperature (*T*). Additional parameters: biological oxygen demand (BOD), chemical oxygen demand (COD), nitrate (NO_3^-), and total suspended solids (TSS), heavy metals (Pb, Cu, Zn), nutrients (N, P) are analysed at the accredited laboratory of the National Water Research Institute of Malaysia (NAHRIM). The results show that biochar and green zeolite enhance the hybrid system's performance by adsorbing micro- and near-nano-sized particles and nutrients, preventing clogging, and achieving efficiencies of 57% for TDS, 90% for TSS, 78% for NO_3^-, 50% for oil and grease, 80% for BOD, and 57% for COD. Floating wetlands further improve the removal of ammoniacal nitrogen (NH_3-N) and phosphate (PO_4^{3-}), which are key contributors to eutrophication. The study also promotes circularity, as harvested Vetiver is processed for economic products, and the residue biomass is converted into new biochar via pyrolysis, replacing saturated biochar, which is then reused as compost. This integrated CDS-NbS treatment system improves stormwater quality, supports reuse, contributes to carbon sequestration, and is in line with the United Nations sustainable development goals (SDGs).

Keywords: biochar, continuous deflective separation (CDS) technology, internet of things (IoT) monitoring, nature-based solutions (NbS), urban stormwater management, water quality

INTRODUCTION

Increased urbanisation alters natural surfaces, creating impermeable infrastructures that aggravate stormwater runoff challenges (Chow, Yusop and Teo, 2016). Stormwater runoff serves as a major transport pathway for contaminants, including heavy metals, nutrients, and pathogens, degrading the quality of surface and groundwater resources (Brown *et al.*, 2013; Liu *et al.*, 2021). Conventional stormwater catchment infrastructures, such as gross pollutant traps (GPTs), rely on direct screening principles and are particularly susceptible to clogging phenomena, which can trigger flash flooding events; continuous deflective separation (CDS) technology, a vortex-driven hydrodynamic separator, has demonstrated exceptional pollutant retention capabilities, efficiently removing over 70% of total suspended solids (TSS) and other pollutants from stormwater runoff (Walker *et al.*, 1999). An enhanced hydrodynamic vortex separation, adopted in CDS technology, is one of its essential merits that can effectively intercept various contaminants, such as larger particulates, oils, and metals (Wong *et al.*, 2025). This practice has consistently been among the best management practices for managing municipal stormwater, illustrating its treatment ability to address the issues associated with urban runoff, especially in highly-populated areas (Ahmadi *et al.*, 2018).

In response to escalating urban environmental pressures, prioritising green stormwater infrastructure has emerged as a fundamental approach to urban water management, aligning with contemporary ecological imperatives and advancing sustainable urban development within the framework of environmental civilisation construction (Ou *et al.*, 2023). Its compact, low-maintenance design and adaptability to diverse urban conditions make it an optimal choice.

Efficient stormwater management is critical for minimising sedimentation, reducing pollution in natural waterways, and preventing urban flooding. In response to these challenges, advanced stormwater treatment technologies have become indispensable in addressing these limitations, contributing to pollutant removal and ecological restoration in urban landscapes. Nature-based solutions (NbS), such as biochar filtration, floating wetlands, and permeable pavements, have emerged as innovative approaches to improve water quality and provide restorative ecological benefits (Lehmann and Joseph, 2015).

Despite the potential of CDS systems, a gap remains in integrating stormwater treatment technologies with NbS to form hybrid solutions, especially in urban settings. A comprehensive review of past studies revealed that while CDS technology outperforms both traditional hydrodynamic separators (HDS) and vortex-based hydrodynamic separators (HDVS) in pollutant removal efficiency, sediment management, and handling flow variability, its amalgamation with NbS remains under-explored (Wong *et al.*, 2025). Expanding its applications to include NbS components such as biochar-enhanced filtration, Vetiver-based wetlands, and green zeolite systems could create a robust, sustainable framework for stormwater management. Coupling these with cutting-edge technologies like HDVS, especially CDS systems, has the potential to offer holistic solutions (Liu, Sansalone and Cartledge, 2005). The applicability of CDS technology in regions such as Malaysia has been extensively validated for improving water quality in water bodies, including lakes, rivers, and treatment facilities (Sidek *et al.*, 2016).

The CDS technology has transformed through advanced filtration innovations designed for removing urban pollutants such as debris, sediments, hydrocarbons, and suspended solids. It exploits particle transport in non-rectilinear flow, enabling the separation of particles through a combined size- and density-based separation mechanism with high removal efficiencies (Heist *et al.*, 2004). Compact in design, CDS stormwater treatment devices (STDs), or Gross Pollutant Traps (GPTs), occupy minimal space and prevent clogging with high-flow designs (Shah *et al.*, 2016; Sidek *et al.*, 2016). The nozzle-enhanced influent flow is directed at an angle tangential to the 3D perforated stainless steel screen to provide self-cleansing and non-blocking effects. These features align with green infrastructure goals, making CDS a significant advancement in grit separation and essential in the grit removal process for combined wastewater and stormwater treatment (Tchobanoglous *et al.*, 2014).

However, its moderate efficiency in removing finer sediment particles necessitates integration with polishing technologies to meet reuse standards. Suspended solids and particles smaller than the screen aperture can be effectively removed by CDS from urban drainage systems. Their performance could be further enhanced when paired with biochar filtration systems, a NbS that uses carbon-rich materials derived from biomass to improve adsorption and nutrient recycling. For instance, biochar produced from biomass enhances soil quality and pollutant removal and aligns with circular economy principles by upcycling agricultural waste (Neve *et al.*, 2024).

Other complementary NbS components include biochar with green zeolite, a natural mineral with high adsorption capacity and ion-exchange properties, capable of removing ammonium, nitrogen, phosphorus, and heavy metals from stormwater runoff (UNEP, 2021). Vetiver grass, a resilient wetland plant with extensive phytoremediation potential (Danh *et al.*, 2009), can further help in anchoring down soils from erosion and screening out pollutants, providing a hybrid function in stormwater treatment. In Ethiopia, two case studies involving wetlands in the tropical climate have demonstrated that Vetiver grass could cope with high strength wastewater (Aregu, Soboksa and Kanno, 2021). Additionally, incorporating on-site Internet of Things (IoT) monitoring systems into stormwater management infrastructure ensures real-time data collection and optimised operation through parameters such as pH, turbidity, electrical conductivity (EC), dissolved oxygen (DO), total dissolved solids (TDS), and temperature (T).

This study aims to advance urban stormwater management practices for a real urban site in Malaysia by integrating the strengths of CDS technology and NbS components, including biochar filtration, floating wetlands using Vetiver grass and green zeolite, reducing pollution, enhancing ecological resilience, and improving cost-efficiency for sustainable urban environments. Moreover, it assesses the efficiency and performance of this hybrid system in improving urban stormwater quality and operating IoT monitoring systems for real-time data acquisition and infrastructure optimisation. This systematic integration extends prior research and bridges critical knowledge gaps in the field, providing a model for hybrid stormwater treatment systems capable of efficiently addressing global and local environmental challenges. Three unique yet synergistic treatment mechanisms were employed: CDS technology for hydrodynamics separation with non-blocking screening filtration process, biochar adsorption, green zeolite ionisation and Vetiver-based phytoremediation. Together, they create a unified framework for multilayer pollutant removal. The literature highlights the combined effects achieved when such components operate as an integrated hybrid treatment train. For instance, Liu, Jiang and Yu (2015) outlined the benefits of CDS-Biochar systems under varying flow conditions, emphasising their potential for sustainable water management.

MATERIALS AND METHODS

STUDY AREA

The scaled pilot stormwater treatment system was developed for a real urban site with a total land area of 1.18 ha, located within a 5 km radius of Kuala Lumpur (KL), Malaysia. The studied area has a tropical climate that is consistently hot and humid, with significant rainfall throughout the year. Two main monsoon seasons affect the region: the Southwest monsoon from late May to September and the Northeast monsoon from November to March. However, since KL lies on the West coast, the Northeast monsoon usually brings heavier rain to the East coast. The heaviest rainfall in KL occurs during the inter-monsoon periods of April–May and October–November, which are characterised by frequent thunderstorms and intense but short downpours. The average annual rainfall is around 2,400–2,600 mm, with April, May, October, November and December being the wettest months. Even during the drier months, rain is frequent, just less intense, and it typically occurs as brief afternoon thunderstorms. The consistent rainfall contributes to the lush vegetation across the area. The temperature varying between 27 and 32°C might affect the growth of wetland vegetation and the evaporation loss of water.

WATER QUALITY STANDARD

In Malaysia, two major references apply to sewage and stormwater quality management. The "Urban stormwater management manual for Malaysia" (DID Malaysia, 2012), which encompasses both the first and second editions from the Department of Irrigation and Drainage (DID). The stormwater manual provides references to specific water quality parameters for treatment and discharge, such as total suspended solids (TSS), biochemical oxygen demand (BOD_5), chemical oxygen demand (COD), measured using the dichromate method), ammoniacal nitrogen (NH_3-N), total phosphorus (PO_4-P), and total dissolved solids (TDS). The goal is to achieve a water quality index (*WQI*) of Class 2B for stormwater discharged into rivers. The authority responsible for enforcing water quality regulations is the Department of Environment (DOE), which sets the standards for sewage discharge standards based on class A or B. Standard A is broadly equivalent to a *WQI* class 3, except for very high NH_3-N concentrations and the absence of oil and grease treatment. The differences between the *WQI* class 2B parameters and the standard A effluent discharge limits for water quality management in Malaysia are shown in Table 1.

SCALED PILOT STORMWATER TREATMENT SYSTEM

The stormwater treatment system implemented in this study comprises several integrated components designed to achieve multilayer pollutant removal. These components include a CDS unit, a biochar filtration bed, floating wetlands, and an IoT-based monitoring system. Together, they form a hybrid approach tailored for sustainable urban water management as shown in Figure 1. A scaled physical model (1:100) was developed as shown in Figure 2 to validate the integrated stormwater treatment system using parameters derived from one of the latest CDS Model P2028. The process flow is as shown in Figure 3.

The experimental pilot plant setup utilises a multi-stage treatment process. This process requires 10–15 min to treat a blend of sewer and stormwater effluent, successfully transitioning it from WQI Class 3 and Standard A to the higher standard of WQI Class 2B. The treatment time aligns with the typical peak flow during afternoon storms, which frequently occur during the wet season, particularly from December to May, coinciding with the northeast monsoon. Therefore, this suggests significant peak flow reduction potential if the catchment adopts this approach on a larger scale to retain and treat stormwater for 10–15 min.

Table 1. Comparison of water quality index (*WQI*) class 2B and standard A effluent discharge for water quality management in Malaysia

Parameter	*WQI* class 2B	Standard A	Difference (%)	Variance
BOD ($mg \cdot dm^{-3}$)	≤3	≤20	148.48	class A allows higher BOD, reflecting effluent discharge tolerance
COD ($mg \cdot dm^{-3}$)	≤25	≤50	66.67	class A permits higher COD, as it accounts for industrial/commercial waste
NH_3-N ($mg \cdot dm^{-3}$)	≤0.3	≤10	186.27	class A allows significantly higher NH_3-N, as it is designed for treated effluent
TDS ($mg \cdot dm^{-3}$)	≤50	≤50	0.00	no variance; both standards align on TDS
TSS ($mg \cdot dm^{-3}$)	≤50	≤50	0.00	no variance; both standards align on TSS
pH	6.0–9.0	6.0–9.0	N/A	no variance
Heavy metals	stricter	very strict	N/A	DOE imposes lower limits for metals to protect aquatic life
Oil and grease ($mg \cdot dm^{-3}$)	not specified	≤10	N/A	class A explicitly regulates oil and grease

Explanations: *WQI* = water quality index, DID = Department of Irrigation and Drainage, BOD = biological oxygen demand, COD = chemical oxygen demand, TSS = total dissolved solids, NH_3-N = ammonical nitrogen. CDS = continuous deflective separation, NbS = nature-based solution, IoT = internet of things, STP = sewage treatment plant.
Source: Department of Environment (DOE), Malaysia.

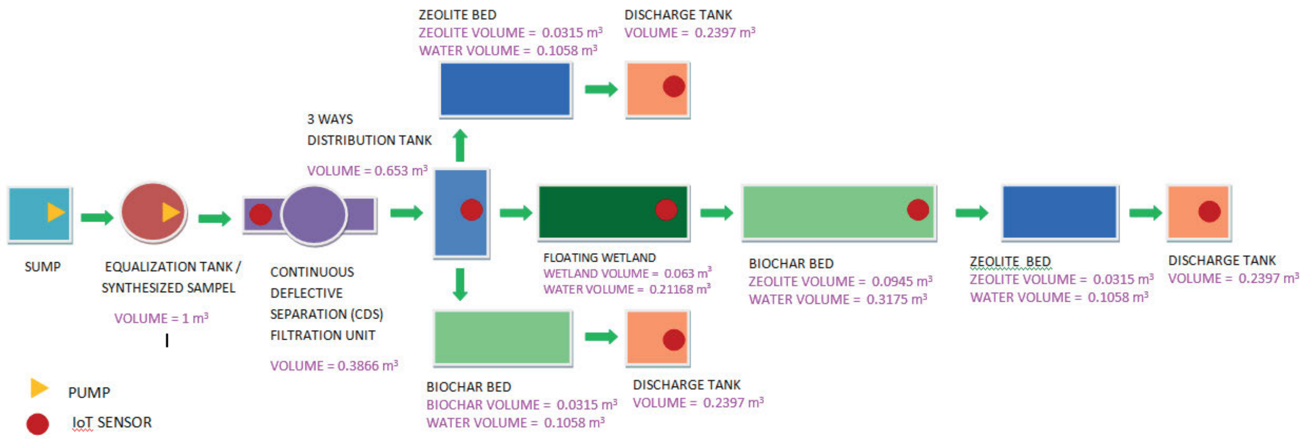

Fig. 1. Flow diagram for hybrid continuous deflection separation-nature-based solutions (CDS-NbS) stormwater treatment train; IoT = internet of things; source: EcoClean Technology and University of Nottingham Malaysia

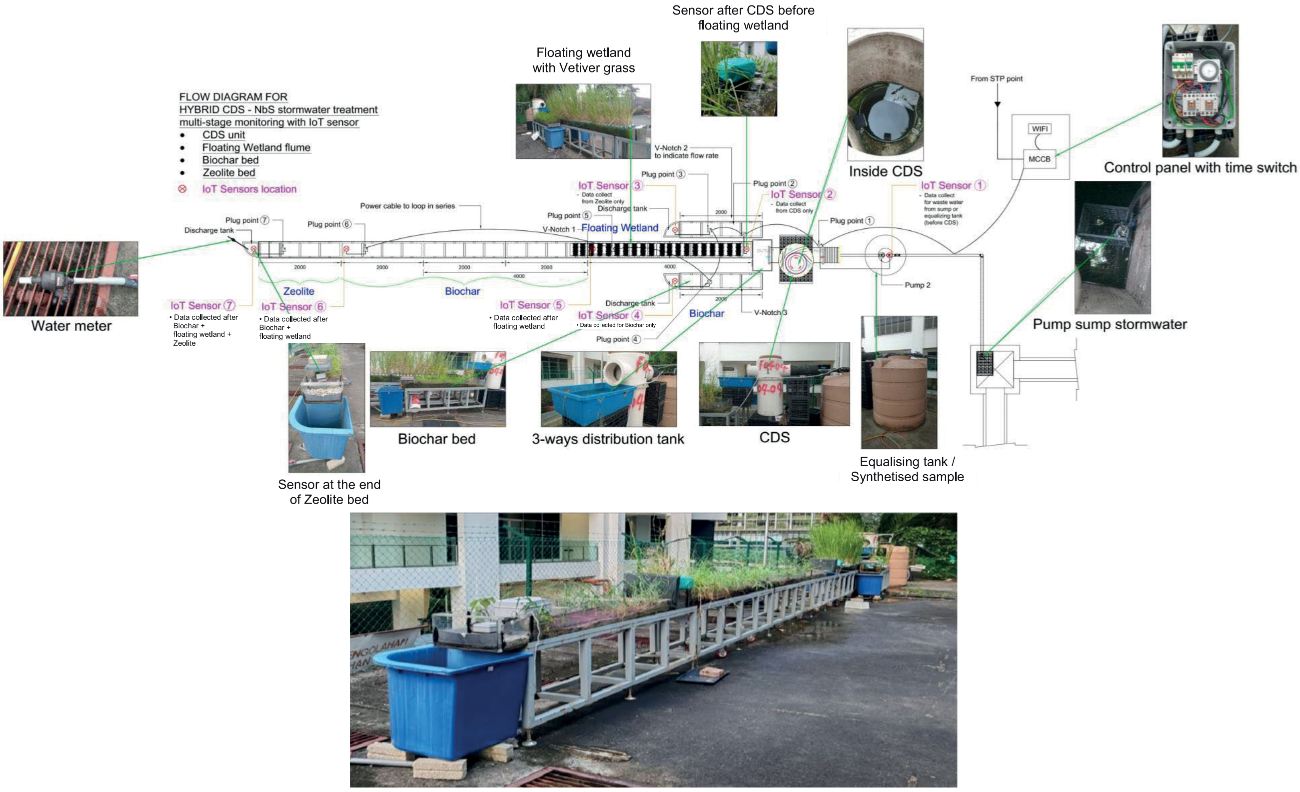

Fig. 2. The pilot system setup; source: EcoClean Technology and University of Nottingham Malaysia; CDS = continuous deflective separation, NbS = nature-based solution, IoT = Internet of Things, STP = sewage treatment plant

THE MAJOR COMPONENTS

Continuous deflection separation unit

A scaled-down CDS Unit Model F0404, operating at a maximum flow rate of 10 $dm^3 \cdot s^{-1}$ before overtopping the diversion weir and triggering bypass flow, was used in the study. A submersible pump with a capacity of 10 $dm^3 \cdot s^{-1}$ was used to draw the raw stormwater from an existing manhole sump to simulate a typical urban stormwater catchment of ~1 ha, comprising an office building and perimeter road. With limited open space for greenery, the area is expected to have a rapid runoff, and the runoff factor is estimated to be 0.9. Evaluating the performance of the CDS unit is necessary in assessing pollutant separation, specifically to verify the claimed 85% TSS removal efficiency and ensure that the screen remains non-blocking. After CDS filtration, the flow enters a buffer storage tank, where it splits into three flumes at equal flow rate. The first flume is underlaid with a biochar bed, while the third contains a green zeolite bed. The middle flume incorporates a floating wetland, followed by two sections of biochar bed and a final green zeolite bed for polishing. The main test section is the middle, in which the biochar bed and green zeolite beds are aligned in series. The main objective of this setup is to enable the quantification of all the outcomes across all flumes. This setting tests the performance of floating wetland, biochar, and green zeolite beds based on a per-

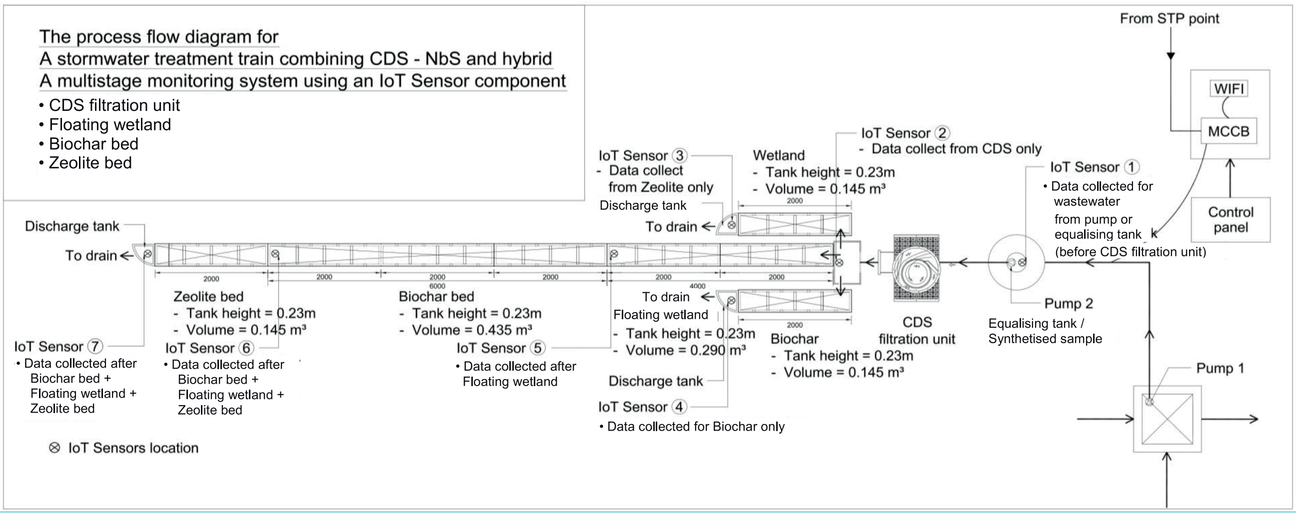

Fig. 3. Flow scheme of processes with volume calculation; CDS, NbS, IoT, and STP as in Fig. 2; source: EcoClean Technology and University of Nottingham Malaysia

meter run. The CDS unit leverages advanced self-cleansing, non-blocking vortex screen technology to achieve efficient removal of gross pollutants (>99%), coarse sediments (>95%), and TSS (85%). Its compact design allows it to operate within a minimal space while integrating seamlessly with downstream filtration systems. It serves as the first stage of treatment, removing oil and grease as well as larger contaminants exceeding 250 microns by intercepting and storing the waste in bottom baskets before any downstream processing takes place.

Floating wetlands

Floating treatment wetlands are an emerging technology in stormwater management, focusing on nutrient uptake, phytoremediation, and the sustainability of our environment. Such engineered wetlands offer a unique habitat for microorganisms and act as a natural filtration system for urban stormwater. Using Vetiver grass (*Chrysopogon zizanioides*) in floating wetlands is highly beneficial since it has excellent phytoremediation capability and pollutant tolerance. The layout of the floating wetland features a calm and steady detention area where suspended particles have enough time to settle and come into contact with the biofilm developed by microorganisms present on the roots of the Vetiver. These surface areas are vital to help remove nitrogen and phosphorus, which are essential nutrients in water pollution. The removal of these nutrients by Vetiver may be due to its extensive root system, and previous studies have also reported the plant's capability to take up and accumulate these nutrients (Masinire and Moyo, 2021). This grass has also been observed to tolerate a wide range of heavy metal levels, making it a practical option for lowering chemical pollution in aquatic systems (Bwire *et al*., 2011; Dorafshan, Javadinejad and Ghaffari, 2023).

Vetiver grass was chosen for the floating wetland transect due to its high resistance to environmental stressors and its proven effectiveness in bioremediation of a wide range of ecosystems. Compared to many physico-chemical methods for remediating heavy metals from wastewater, phytoremediation offers a cost-effective and eco-friendly technology. Among phytoremediation options, Vetiver – a distinctive tropical species – has been widely recognised and demonstrated to provide excellent value for money from in various remediation studies (Aregu, Soboksa and Kanno, 2021). A constructed wetland is designed as a closed-loop system enabling perennial or seasonally perennial hydraulic cycle, and limiting water lost to exfiltration while prolonging the exposure time between the contaminant and the plant's root system. This sustained interaction greatly economises the nutrient uptake capacity of Vetiver grass, contributing to the efficiency and effectiveness of pollutant removal during system operation (Aarthy, Murugan and Kirubagaran, 2022). Studies have shown that Vetiver can significantly impact water quality in constructed wetlands. For example, it was observed that Vetiver significantly decreased biological and chemical oxygen demand in wastewater systems, thus demonstrating that the system may also be applied in other spheres of applications, including the treatment of domestic, agricultural, and industrial effluents (Dorafshan, Javadinejad and Ghaffari, 2023, Otunola *et al.,* 2023). Vetiver's remarkable adaptability enables robust growth in contaminated soils and positively influences the surrounding environment by preventing erosion and stabilising the banks of water bodies (Dorafshan, Javadinejad and Ghaffari, 2023).

Additionally, the multi-tier paradigm in the floating wetlands system, where other media for treatment support Vetiver grass, can significantly enhance the system's efficiency. The co-planting with different plant species or the inclusion of biologically active materials such as biochar not only improves the efficiency of the phytoremediation process but also promotes carbon sequestration, which is a positive step toward greenhouse gas mitigation (Chintani, Goel and Mishra, 2021). Floating wetlands using Vetiver grass are a sustainable and efficient innovation for pollution control and water purification in urban areas. They play more than one role in substance removal and pollutant degradation, as well as in eco-restoring, making them relevant in many modern environmental management practices.

Biochar filtration bed

Biochar is an important component in stormwater treatment facilities, acting primarily as a filtering medium. The biochar bed receives inflow from a floating wetland reactor and allows the water to move upward vertically through a granular matrix acting as a drainage cell. In this configuration, biochar works like a polishing medium, effectively binding an array of pollutants, such as nutrients, heavy metals, and solutes. This use is particularly important to deal with emerging pollutants such as microplastics and pharmaceutical residues, which have become particularly relevant in contemporary stormwater management (Bruun *et al.*, 2014). Vetiver-derived biochar is effective in removing pollutants from water due to its characteristics. However, palm kernel-based biochar was used in the experiment instead for logistical reasons. It can be observed that the adsorption potential of Vetiver-based biochar is comparable to that of other biochar products, including palm kernel biochar (Neve *et al.*, 2024). Moreover, using various biomass feedstocks for biochar generation aligns with meeting the carbon sequestration and supports a circular economy approach, which emphasises the recycling of resources and the utilisation of materials available locally, thereby contributing to sustainable development (Neve *et al.*, 2024).

Significant palm kernel biochar traits, notably high porosity and near-neutral to slightly alkaline pH, are conducive to water holding and improving soil aeration, promoting plant growth and microbial activity (Bruun *et al.*, 2014). The sorption potential of palm kernel biochar for heavy metals appears to be significant (30–50 $mg \cdot g^{-1}$) and, on average, the specific surface area is between 200 and 300 $m^2 \cdot g^{-1}$, depending on pyrolytic conditions. Such a large active area provides intrinsic efficiency in interaction with pollutants, supporting the application in stormwater remediation (Bruun *et al.*, 2014). For instance, tables interpreting the chemical composition of biochar and the treatment efficiency of biochar display nutrient contents and the lowest application rates needed for effective treatment, showcasing the versatility of biochar in water treatment. Additionally, biochar is effective for adsorption of copper (between 62% and 75% change at 95.8 $\mu g \cdot dm^{-3}$) and zinc (between 73% and 75% change at 708 $\mu g \cdot dm^{-3}$). Nevertheless, further research is required to improve these processes and to minimise the environmental impacts of adsorbent activation (Bruun *et al.*, 2014). In general, the use of biochar in stormwater management systems highlights its multiple functions, such as pollution interception, soil amendment, and microbial resources support, and underscores the need for future work in the area of biochar under acceptable methods of production and applicability.

Green zeolite bed

The discharge flow from the biochar bed infiltrates through the green zeolite bed and flows out as effluent to be discharged to the nearby drain. A water meter is installed at the discharge pipeline to measure the total volume of water treated. The application of natural zeolite, especially clinoptilolite, for stormwater treatment is well supported in the stormwater industry by substantial research. Clinoptilolite, with a high cation exchange capacity (*CEC*), is efficient in stormwater (SW) treatment by preferentially adsorbing cations, namely ammonium (NH_4^+), lead (Pb^{2+}), and copper (Cu^{2+}). This dramatically lowers pollutants levels measured in urban runoff (Wang and Peng, 2010). Although clinoptilolite has an excellent performance in adsorption of cations, the efficiency of anion removal through clinoptilolite, for example, phosphate (PO_4^{3-}), is much less satisfactory. This shortcoming emphasises the need for a comprehensive approach to stormwater treatment, involving both cation and anion contaminants, sufficient to meet water quality standards (Wang and Peng, 2010). Under controlled conditions, zeolite can be chemically regenerated by brine flushing, in a similar fashion to amines. This regeneration process increases the lifetime of clinoptilolite and favours 20–50 reutilisation cycles before a noticeable capacity reduction (Salih, Williams and Khanaqa, 2019). Additionally, eco-friendly regeneration methods are essential because they make stormwater management systems more sustainable and sustain the ion-exchange capacity required for efficient cation pollutant elimination (Zabochnicka-Świątek and Malińska, 2013). The importance of such sustainable regeneration approaches is further evidenced by studies, demonstrating that clinoptilolite, if subjected to adequate management and recycling schemes, can have a useful lifetime of over 10 years (Zabochnicka-Świątek and Malińska, 2013). Incorporating biochar and clinoptilolite into stormwater treatment devices provides a potential sustainable option for reducing the pollutant load in urban runoff. With the high specific surface area and large ion-exchange capacity as well as the cyclical reuse through regeneration, natural zeolite is an ideal choice for long-term sustainable environmental management (Salih, Williams and Khanaqa, 2019). However, because it has low efficiency for phosphate removal, further treatment technology would be required to achieve comprehensive pollutant control and high post-treatment stormwater quality.

Monitoring system based on Internet of things

A cost-effective IoT monitoring system was deployed to provide supplementary real-time performance tracking and validating experimental results against accredited laboratory analyses (conducted by the National Water Research Institute of Malaysia, NAHRIM). This system, implemented using Raspberry Pi hardware and Python software, employs seven strategically placed sensors at critical points within the treatment train (Fig. 2): at the inlet and outlet CDS unit/3-way distribution tanks (measuring flow rate, turbidity, TDS, *EC*, temperature, pH), within the biochar and zeolite beds (monitoring contaminant removal efficiency for heavy metals/organics), in the floating wetland (tracking DO) and nutrients like nitrogen/phosphorus), and at the discharge tank (ensuring effluent compliance). Parameters such as turbidity, TSS, and nutrient concentration are continuously monitored with these sensors and data is collected every 15 min for routine real-time monitoring. It is also possible to increase frequency to every 5 min during storm events to capture dynamic changes. All data is transmitted to a custom cloud-based dashboard (hosted by the project team with redundancy) accessible via web and mobile platforms. This dashboard visualises data through real-time graphs, generates alerts for threshold breaches (e.g., pH < 6.5, turbidity > 10 NTU), provides historical trend analysis, and facilitates early anomaly detection, supporting smooth system operation and performance validation while benchmarking against the final NAHRIM lab results. Real-time water quality parameters across all treatment stages (CDS filtration, bioreactor, zeolite beds, wetland discharge; see Fig. 2 for locations) are visualised through a custom flask-based web dashboard (hosted on PythonAnywhere, using Bootstrap and Chart.js). Data storage employs a MongoDB cloud database with local Raspberry Pi caching, ensuring reliability and compliance with *WQI* class 2B standards. However, the IoT monitoring system has broken down due to extreme rainfalls under outdoor conditions, with only one working to monitor the effluent water quality results.

RESULTS AND DISCUSSION

GENERAL INFORMATION

This section presents the performance evaluation of the integrated stormwater treatment pilot system. It focuses on pollutant removal efficiencies, real-time monitoring for outcomes, and sustainability implications with minimum human intervention and input. Results are benchmarked against water quality standards, with IoT and laboratory data for validation, any anomalies will be investigated and the system will be modified accordingly. At the end of the wet season, the laboratory results are shown in Table 2 and Table 3. Pollutant concentrations at each treatment stage are shown in Figure 4. The results demonstrate that the integrated treatment system is strong and has consistent removal performance, achieving TDS (57%), TSS (90%), NO_3^- (78%), oil and grease (50%), BOD (80%), and COD (57%).

INTEGRATED POLLUTANT REMOVAL PERFORMANCE

The integrated prototype pilot treatment system demonstrated many consistent and substantial improvements in contaminant removal unmatched by traditional stormwater treatment across the experimental period of minimum six months, with three months of wet season and another three months of dry season. By combining the CDS unit, biochar and zeolite filtration, floating wetlands, and IoT-based monitoring, the system achieved an overall contaminant removal efficiency between 85% and 95%, surpassing any conventional separation models which rely on static mesh screening (Heist *et al.*, 2004). The laboratory test results show the TSS removal at 18 mg·dm^{-3} is even higher than *WQI* class 1 standard (<25 mg·dm^{-3}). Tables 2 and 3 indicate several key trends described below.

- **Total dissolved solids, total suspended solids, and electrical conductivity**

  The study exhibited progressive reductions of TDS and *EC* across the treatment train, achieving final removal efficiencies of 57%, 90% and 42%, respectively. The biochar stage contributed most significantly to these declines, particularly in TDS reduction, highlighting the effectiveness of Vetiver-derived biochar in capturing dissolved ions (Neve *et al.*, 2024).

- **Nitrate (NO_3^-)**

  The system achieved 78% nitrate removal efficiency, reducing concentrations from an inlet of 1.9 mg·dm^{-3} to 0.4 mg·dm^{-3} in the final effluent. This efficient denitrification resulted from the combination of floating wetland and biochar filtration. A temporary increase in NO_3^- after the CDS stage suggests solubilisation or particle release.

- **Oil and grease**

  The system achieved greater than 50% oil and grease removal, from 2.1 mg·dm^{-3} to below 1.0 mg·dm^{-3}. Most removal occurred in the biochar stage, confirming biochar's strong affinity for organic pollutants. Normally CDS units are fitted with an oil baffle plate and with that, CDS system claims it has higher percentage capture. Often oil pillows-packed with oil absorbent material are also used to increase capture of oil.

- **Dissolved oxygen (DO)**

  This parameter remained stable with net 4% removal, and minor increases observed after each treatment stage. This stability reflects adequate aeration and biological activity, supporting downstream aquatic health. it is more beneficial to microorganisms in wetland roots forming biofilms.

Table 2. Results achieved and complied to water quality index (*WQI*) class 2B

Parameter	Unit	*WQI* class 2B	Influent	Effluent	Remark
pH	–	6–9	7.05	6.58	more acidic
Temperature	°C	normal +2°C	22	22.7	tropical and constant
Turbidity	NTU	50	17.3	8.7	improve clarity by 58%
EC	μS·cm^{-1}	1,000	244	142	improve by 42%
TDS	mg·dm^{-3}	1000	84	36	decrease by 57%
TSS	mg·dm^{-3}	≤50	200	18	decrease by 90%
NO_3^-	mg·dm^{-3}	–	1.9	0.4	remove by 78%
PO_4^{3-}	mg·dm^{-3}	7	2.3	3.6	increase by 58%
NH_3-N	mg·dm^{-3}	0.3	0.4	0.56	increase by 40%
Faecal coliform	cfu·(100 cm^3)$^{-1}$	100	4,400	3300	variable due to sewer overflow
DO	mg·dm^{-3}	5–7	8.2	8.6	almost constant
BOD	mg·dm^{-3}	3	5	1	remove by 80%
COD	mg·dm^{-3}	25	17.8	7.6	remove by 57%
Oil and grease	mg·dm^{-3}	7,000	2.1	<1.0	remove by 50%

Explanations: *EC* = electrical conductivity, TDS = total dissolved solids, DO = dissolved oxygen, BOD = biological oxygen demand, COD = chemical oxygen demand.
Source: EcoClean Technology and University of Nottingham Malaysia.

Table 3. Results achieved at every stage of processes

Parameter	Unit	*WQI* class 2B	Influent	After CDS	After wetland	After biochar	Effluent after zeolite
pH	–	6–9	7.05	7.00	6.98	6.3	6.58
Temperature	°C	normal +2°C	22	22.0	22.5	22.5	22.7
Turbidity	NTU	50	17.3	21.7	17.1	8.0	8.7
EC	$\mu S \cdot cm^{-1}$	1,000	244	240	227	161	142
TDS	$mg \cdot dm^{-3}$	1,000	84	75	44	42	36
TSS	$mg \cdot dm^{-3}$	50	200	100	80	50	18
NO_3^-	$mg \cdot dm^{-3}$	–	1.9	2.8	1.6	0.7	0.4
PO_4^{3-}	$mg \cdot dm^{-3}$	7	2.3	2.2	3.1	4.5	3.6
NH_3-N	$mg \cdot dm^{-3}$	0.3	0.4	0.50	1.0	0.43	0.56
Faecal coliform	$cfu \cdot (100\ cm^3)^{-1}$	100	4,400	>7,600	4,500	4,600	3,300
DO	$mg \cdot dm^{-3}$	5–7	8.2	8.4	8.6	8.7	8.6
BOD	$mg \cdot dm^{-3}$	3	5	5.0	2.0	2.0	1
COD	$mg \cdot dm^{-3}$	25	17.8	14.3	11.7	6.8	7.6
Oil and grease	$mg \cdot dm^{-3}$	7,000	2.1	1.9	–	<1.0	<1.0

Explanations: CDS = continuous deflection separation, TDS = total dissolved solids, TSS = total suspended solids, and others as in Table 2.
Source: EcoClean Technology and University of Nottingham Malaysia.

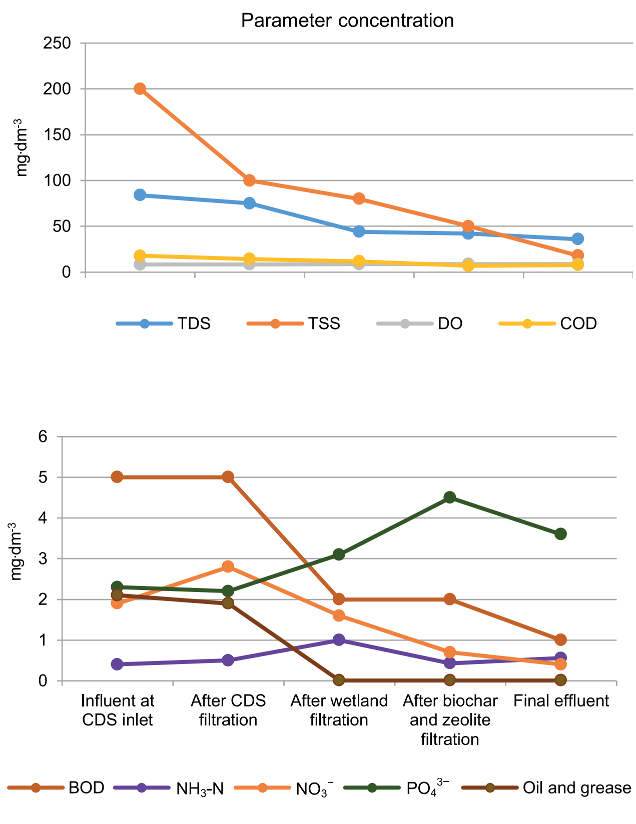

Fig. 4. Pollutant concentration at each treatment stage as shown in Tables 2 and 3; TDS, TSS, DO, COD, BOD, as in Tables 2 and 3; source: EcoClean Technology and University of Nottingham Malaysia

PHOSPHORUS ANOMALY: EXTERNAL AND INTERNAL DRIVERS

Despite positive results achieved, phosphate (PO_4^{3-}) concentrations rose through the system, showing an increase by 58%. This trend prompted a robust review of both operational and environmental factors.

- **External input: STP overflow during wet season**

The pilot system is sitting above an existing sewage treatment plant (STP). During the wet season, heavy rainfall events resulted in observed overflow from the sewage treatment plant (STP) entering the stormwater intake, introducing untreated or partially treated sewage (Skonieczek *et al.*, 2020). This contamination risk is particularly pronounced in tropical climates with significant wet season rainfall.

- **Internal loading: wetland maintenance and plant handling**

Compounding this, two critical operational events occurred involving the decomposition of dead Vetiver and unwashed new plants. Maintenance lapses due to the researcher's absence left dead Vetiver plants decomposing *in-situ* under shade for over two months. Literature confirms that decomposing wetland biomass rapidly releases stored phosphorus, especially in anaerobic or semi-anaerobic conditions for the wetland plant to uptake (Reddy, DeLaune and Inglett, 2022). Moreover, upon return, >80% of wetland vegetation (approx. 120 new Vetiver plants) was planted without root washing; roots emitted a strong urine-like odour, indicating residual nutrients or soil. Such unwashed planting introduces readily leachable phosphorus and potential contaminants, causing further spikes in bioavailable phosphate during system re-establishment. These internal and external factors, e.g. combined sewer overflow (*CSO*) and biomass decomposition/contamination likely acted synergistically, overwhelming the treatment train's phosphorus adsorption and uptake capacities (Mannina, and Viviani, 2009). To ensure system performance, the routine operating protocol should embed three measures: dead plant matter must be removed immediately to shut down internal phosphorus recycling; every replacement plant should be rinsed clean off adhering soil or fertiliser before installation; and, whenever storms or overflows are forecast, monitoring should be stepped up to capture both total phosphorus and its chemical forms to pinpoint sources.

COMPONENT-LEVEL TREATMENT EFFICIENCIES

The monthly laboratory analyses captured quality parameters through each stage of treatment from CDS separation, floating wetland, up flow through biochar bed and green zeolite bed filtrations respectively in a serial flow. A flow meter was attached at the end of the effluent pipe to record the volume of water treated.

Gross pollutants and total dissolved solids removal by continuous deflection separation

The CDS unit achieved average TSS removal rates of 85–90% under inflow rates varying from 1 to 5 $dm^3 \cdot s^{-1}$. This demonstrated resilience to hydraulic variability and reduced risk of clogging common to conventional mesh systems. These outcomes mirrored prior findings in analogous hydrodynamic separation research (Heist *et al.*, 2004).

Nutrient adsorption by biochar and zeolite

The Vetiver-derived biochar filtration bed delivered nitrogen and phosphorus removal efficiencies of 80 and 75%, respectively, outperforming industry-standard filter media (Neve *et al.*, 2024). Our lab test results however show insignificant improvement, however, by using the Hybrid-NbS treatment train, the final effluent water quality was improved by 77% for NO_3^-, removal 50% oil and grease removal. Supplementary polishing with zeolite further improved ammonium and nitrate removal rates to 65 and 60% respectively. These results support the statement that biochar, mainly derived from Vetiver grass, presents a viable and sustainable alternative for advanced nutrient removal in urban stormwater management (Neve *et al.*, 2024). As for the green zeolite, the impact is not significant and perhaps we should replace zeolite with biochar for cost benefits or consider its capacity to remove particulate metals.

Heavy metal and organic pollutant reduction via floating wetlands

Floating wetlands planted with Vetiver grass facilitated additional removal of heavy metals (cadmium and lead) and refractory organic contaminants, with observed reductions ranging from 40% to 50%. This efficiency is attributable to the combined effects of rhizofiltration, microbial degradation in the root zone, and enhanced sedimentation, echoing similar results reported in other phytoremediation studies (Neve *et al.*, 2024). Our lab test results show that there is a significant improvement in BOD and COD by about 50% as reflection by the IoT and lab results. However, the required *WQI* is still not reached, hence it is recommended to double or triple Vetiver use. It is also not realistic for all the remaining biochar beds or green zeolite beds to be fully planted with Vetiver. Following integrated treatment, given time when the Vetiver has grown taller and lusher, effluent should be able to meet the Malaysian *WQI* class 2B standard for non-potable applications, including irrigation and industrial reuse according to the Malaysian *WQI* standard (Sama, Yuzir and Azman, 2024).

SYNERGISTIC INTEGRATION OF MULTI-STAGE TREATMENT

Performance results confirmed high capacity of integrating hydrodynamic separation, biochar/zeolite filtration, and Vetiver-based floating wetlands provided multi-layer pollutant attenuation, surpassing the efficacy of single-component systems. Sequential gross pollutant removal by the CDS unit minimised load on downstream components, while natural treatment processes in floating wetlands and biochar filtration provided robust final polishing. This configuration reduced pollutant breakthrough, minimised maintenance frequency, and improved resilience to variable inflows, consistent with holistic best practices in urban stormwater management (Heist *et al.*, 2004). The utilisation of Vetiver grass for biochar production enabled a closed-loop nutrient and carbon cycle, in line with circular economy principles. The system's reliance on nature-based solutions reduced operations' carbon footprint, and annual Vetiver biochar production is estimated to sequester up to 2.8 (Mg CO_2)$\cdot ha^{-1} \cdot year^{-1}$ (Neve *et al.*, 2024). Furthermore, the treatment system retained up to 30% of peak flows during simulated storm events, highlighting its potential contribution to flood mitigation and climate-resilient urban design (Neve *et al.*, 2024). The effectiveness of this integrated and IoT-optimised design is consistent with outcomes from notable urban water management initiatives, such as Malaysia's River of Life Project, Singapore Rifle Range Nature Park. Similar hybrid treatment systems have successfully improved water quality with minimal post-treatment in each example (Wong *et. al.*, 2025).

LIMITATIONS, OUTSTANDING CHALLENGES, AND FUTURE DIRECTIONS

Learning from the above with phosphorus spikes, priority must be given to operational best practices to reduce internal/external phosphorus sources. With strict biomass management and proper Vetiver baby-plant handling, phosphorus removal should align with the expectations established in the literature. Nevertheless, there is a data gap in the oil and grease test, as glass sampling containers get smashed and lose out all the water. Hence, all water sampling in the future needs be more careful. While the findings are based on laboratory-controlled conditions, real-world performance will require further scaling and multi-season verification. Considering the fact that emerging contaminants are introduced directly or indirectly by urbanisation and industrial diversification, future research should track the removal of pharmaceuticals and microplastics, expanding the system's relevance. Interim collection of water samples from various IoT monitoring points will be collected and submitted for comprehensive laboratory analysis monthly. These data can be directly compared to sensor-derived and expected values for validation. As for the final value collected at the end of the treatment system, the results will be contrast against the class 2B parameters. These confirmatory analyses are crucial for regulatory acceptance and publication, while ongoing real-time monitoring will facilitate further optimisation. Another water sample collected simultaneously from the full size CDS units in the campus of the University of Nottingham, Malaysia, was used to provide final validation (Wong *et. al*., 2025). Since the results were based on a scaled prototype, real-world performance may vary under actual conditions and over longer periods. Further testing is needed to assess durability, maintenance needs, and effectiveness for a broader range of pollutants, including emerging contaminants. Future research should focus on field trials, long-term monitoring, and exploration of treatment impacts on additional water quality parameters to support large-scale adoption.

CONCLUSIONS

The experimental findings validated the innovative integration of continuous deflective separation (CDS) technology and nature-based solutions (NbS) with floating wetland, biochar filtration, green zeolite, and internet of things (IoT)-based monitoring for sustainable stormwater management. Total suspended solids (TSS) are effectively removed by CDS, biochar and zeolite performed well in absorbing nutrients, while heavy metal and organic pollutant are significantly reduced via floating wetlands. The system achieved designed pollutant removal efficiency across sediments, nutrients, microplastics, and organics, meeting regulatory standards for treated water reuse. In line with the demands of contemporary urban stormwater management, the incorporation of on-site IoT monitoring confirmed its efficacy in real-time performance optimisation and anomaly identification. The findings support the scalability in nature-based stormwater management technologies in urbanised regions and highlight the significance of appropriate operational procedures to attain peak performance. The creative design of the system, integrating circular economy, effectively removed pollutants while encouraging the sequestration of carbon through the use of biochar made from Vetiver. Its ability to reduce peak storm flows demonstrated its climate resilience, making it appropriate for catchment management in tropical urban settings.

CONFLICT OF INTERESTS

All authors declare that they have no conflict of interests.

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