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Comparative performance and statistical analysis of DEGBR and EGSB reactors for treating high-strength poultry slaughterhouse wastewater

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Abstract
High-rate anaerobic bioreactors (HRABs) are increasingly employed for treating high-strength wastewaters due to their ability to handle elevated organic loading rates (OLRs) at reduced hydraulic retention times (HRTs). This study compares the performance of two HRAB configurations the up-flow Expanded Granular Sludge Bed (EGSB) and the down-flow Expanded Granular Bed Reactor (DEGBR) for poultry slaughterhouse wastewater (PSW) treatment. Both systems included a biological pre-treatment stage and post-treatment with a membrane bioreactor (MBR). The DEGBR consistently outperformed the EGSB, achieving COD, TSS, and FOG removals of 87%, 92.5%, and 89.4%, respectively, versus 53.9%, 68.4%, and 66.9% for the EGSB. When integrated with pre-treatment and MBR polishing, the DEGBR-based system achieved > 99% removal across all parameters. Statistical analysis confirmed the significance of these differences ($p < 0.05$). These results demonstrate the DEGBR–MBR system's robustness, stability under variable loading, and suitability for decentralised PSW treatment in resource-limited settings, offering a scalable and energy-efficient solution for broader industrial wastewater applications.

Keywords Down-flow expanded granular bed reactor (DEGBR), Expanded granular sludge bed reactor (EGSB), High-rate anaerobic bioreactor (HRAB), Poultry slaughterhouse wastewater (PSW), Membrane bioreactor (MBR), Organic loading rate (OLR), Hydraulic retention time (HRT), Anaerobic digestion, Wastewater treatment, Bioreactor performance comparison

1 Introduction

Arid regions are experiencing an escalating water crisis [1], with some countries losing up to 37% of their potable water supply due to ageing infrastructure and inadequate maintenance [19, 21]. Industrial activities, particularly in the mining, manufacturing, and agro-processing sectors, are among the leading contributors to deteriorating surface water quality. These sectors generate vast quantities of high-strength wastewater [24], and the inability to adequately treat and manage these effluents has resulted

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in widespread eutrophication of water bodies [6]. For example, it is estimated that over 60% of South Africa's water resources are impacted by inadequately treated wastewater, contributing to odour, discoloration, and microbial contamination in receiving environments [25–27].

Poultry slaughterhouse wastewater (PSW) is a particularly challenging waste stream, characterised by high concentrations of organic pollutants including chemical oxygen demand (COD), biological oxygen demand (BOD), fats, oils, and grease (FOG), as well as suspended solids and pathogens [2, 3, 5, 6, 20, 29]. To meet environmental discharge standards, such as those set by the Department of Water Affairs in South Africa, robust treatment systems are required that can consistently reduce contaminant levels under fluctuating influent quality [13].

High-rate anaerobic bioreactors (HRABs) have gained increasing recognition for their efficiency in treating high-strength wastewaters due to their compact design [17], low energy requirements, reduced sludge generation, and an ability to handle high organic loading rates (OLRs) at short hydraulic retention times (HRTs) [23, 30, 32, 37]. Common HRAB configurations include the Up-flow Anaerobic Sludge Blanket (UASB), Expanded Granular Sludge Bed (EGSB), Static Granular Bed Reactor (SGBR), and, more recently, the Down-flow Expanded Granular Bed Reactor (DEGBR), a system inspired by the SGBR design [36].

The SGBR was developed by Ellis and Evans [14] at Iowa State University as a simple, downflow anaerobic reactor relying on a dense bed of granular sludge for organic degradation without the need for mechanical mixing or complex internal components [14]. Its ease of operation, cost-effectiveness, and stable performance made it attractive for decentralized treatment of various industrial wastewaters, including those from slaughterhouses and dairy operations [15, 33, 34]. However, when treating lipid-rich effluents such as PSW the SGBR exhibited operational shortcomings [10]. Specifically, gas entrapment, sludge compaction, and the formation of dead zones within the granular bed were frequently reported, impairing hydraulic flow and biogas release [31, 32].

Motivated by these challenges, Njoya [31] introduced a targeted modification to the SGBR, resulting in the DEGBR, by integrating a controlled recirculation loop. This adjustment enabled limited bed expansion, enhanced mixing and contact between,the sludge, and influent, culminated in alleviating the accumulation of entrapped gases. The DEGBR retained the SGBR's operational simplicity while demonstrating significantly improved performance in the treatment of PSW under high lipid and organic loads [12, 31].

In addition, coupling anaerobic reactors with Membrane Bioreactors (MBRs) has emerged as an effective effluent polishing strategy to meet increasingly stringent discharge regulations. MBRs enable additional removal of suspended solids, nutrients, and pathogens, thus enhancing the sustainability and reuse potential of the treated effluent [16, 28, 35].

Given these developments, this study aimed to **(1)** compare the treatment performance of the EGSB and DEGBR systems for PSW under identical operating conditions, **(2)** evaluate their effectiveness as standalone high-rate anaerobic reactors and as part of integrated treatment trains incorporating enzymatic pre-treatment and MBR polishing, and **(3)** use statistical analyses to determine the significance of observed differences and quantify process stability under variable loading conditions. By addressing these objectives, the study provides a robust, evidence-based assessment of the suitability of the DEGBR configuration as a cost-effective and scalable solution for decentralized treatment of high-strength, lipid-rich wastewaters in resource-constrained settings.

2 Materials and methods

2.1 Experimental setup

A lab-scale wastewater treatment system was designed to compare the performance of a DEGBR and an EGSB reactor for treating PSW as shown in Fig. 1. Each system integrated a pre-treatment unit, a bioreactor (EGSB or DEGBR), and a post-treatment MBR. The reactors were operated under controlled mesophilic conditions (35–37 °C) and monitored to ensure identical influent characteristics and environmental parameters.

To ensure fair comparison, both systems received PSW from the same source, were inoculated using identical UASB-derived sludge, and maintained under identical environmental and operational conditions (e.g., temperature, pH, influent quality). Reactors were operated in parallel and were sampled at the same frequency.

2.2 Pre-treatment setup and operation

To mitigate fats, oil, and grease (FOG)-induced clogging and enhance biodegradability, a biological delipidation agent, Eco-flush™ (0.01% v/v), was added to the batch-fed pre-treatment tank. The Eco-flush™, a hydrolysis remediation product composed of an enzyme and microbial blend (40%), organic nitrogen (3%), potassium (4%), organic carbon (10%), organic matter (31%), and water (12%) (Table 1), was supplied by ErgoFito (Pty) Ltd., Cape Town, South Africa. The raw poultry slaughterhouse wastewater (PSW) with Eco-flush™ was aerated for 24 h using air spargers to promote the hydrolysis of FOG and odour reduction. This was followed by a 24-h settling period to reduce dissolved oxygen concentrations, rendering the pre-treated effluent suitable for subsequent anaerobic treatment. The complete pre-treatment process required approximately 48 h for each batch preparation.

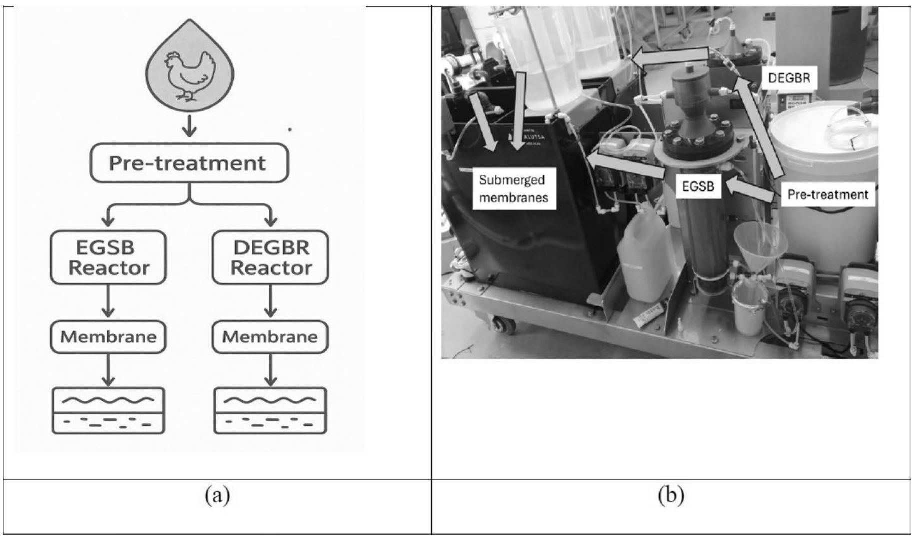

Fig. 1 **a** Schematic of the bench-scale dual-train system with EGSB and DEGBR reactors and membrane filtration for poultry slaughterhouse wastewater. **b** Lab setup showing pre-treatment, reactors, and submerged membrane units

Table 1 Composition of the Eco-flush™ _Bioremediation Agent

Component	Content (%)
Enzyme and microbial blend	40
Organic nitrogen (N)	3
Potassium (K_2O)	4
Organic carbon (C)	10
Organic matter	31
Water	12

Table 2 Reactor Operating Conditions

Reactor	COD_in Feed Range (g COD/L)	OLR Range (g COD/L·day)	Approximate HRT Range (hours)	Approximate Average HRT
EGSB	4 → 10	4 → 18	~ 5.3 → 60	~ 18 h
DEGBR	4 → 10	18 → 44	~ 2.2 → 13.3	~ 5.4 h

2.3 Reactor configuration and operation

The up-flow EGSB and down-flow DEGBR were constructed using transparent PVC columns with comparable dimensions, each having an inner diameter of 0.0814 m, a height of 0.612 m, and a working volume of 2 L, which was used during the experimental operation of the lab-scale system. The selected HRT ranges were informed by prior studies reporting optimal treatment efficiency for high-strength poultry slaughterhouse wastewater and other lipid-rich industrial effluents at comparable retention times [12, 31]. Organic loading rates (OLRs) ranged from 4 to 18 g COD/L·day for the EGSB and from 18 to 44 g COD/L·day for the DEGBR. Both reactors were operated under mesophilic conditions (35–37 °C), with minor fluctuations attributable to laboratory ambient temperature variation, ensuring stable microbial activity and valid performance comparisons.

Granular sludge used for inoculation was obtained from Anheuser-Busch InBev SA (Newlands Brewery, Cape Town) and stored in a sealed 20 L polystyrene container at 28 °C until use. Both reactors were inoculated in parallel with the same sludge to ensure a consistent microbial consortium. Approximately 400 g of pea gravel was placed in the base of the DEGBR to retain granules during downflow operation. To accelerate microbial acclimatization and biofilm development, approximately 400 mL of granules were supplemented with 200 mL of baby formula at 0.75 g/mL as an additional carbon/nitrogen source. The reactors were maintained under gentle recirculation for 72 h prior to the introduction of pre-treated PSW, allowing the microbial community to acclimate and reducing the risk of reactor shock during start-up. PSW was sourced from a local poultry slaughterhouse facility and refrigerated at 5 °C prior to use to minimise compositional changes before feeding. The specific operating conditions for both reactors during the experimental period are summarised in Table 2.

2.4 Membrane bioreactor (MBR) configuration

The membrane tank, constructed from high-density polyethylene (HDPE), comprised a 37.3 L anoxic zone and a 75.7 L aerobic zone housing a submerged ultrafiltration (UF) membrane unit (NADIR® UP150, Microdyn-Nadir GmbH, Wiesbaden, Germany). The membrane was manufactured from hydrophilic polyethersulfone (PES) with a nominal

Table 3 Membrane and Module Specifications

Parameter	Specification
Membrane Characteristics	
Membrane	NADIR® UP150
Membrane Polymer	Polyethersulfone (PES)
Nominal Pore Size	0.04 μm
Preservative	Glycerine 20% / Sodium benzoate 3%
Module Specifications	
Housing Material Options	Polyvinyl chloride (PVC)
Drainage Layer	Polyester (PET)
Nominal Membrane Area	0.37 m^2
Physical Dimensions	
Dry Weight	6.73 kg
Length	315 mm
Width	182 mm
Height	696 mm

Table 4 Analytical Methods

Parameter	Method
Temperature	EPA Method 9040C
TSS	EPA Method 160.2
COD	EPA Method 410.4
FOG	EPA Method 10,056

pore size of 0.04 μm and a nominal membrane area of 0.37 m^2. The unit incorporated a polyvinyl chloride (PVC) housing and a polyester (PET) drainage layer (Table 3). The dry weight of the membrane module was 6.73 kg, with physical dimensions of 315 mm × 182 mm × 696 mm. Prior to continuous operation, the membrane unit was conditioned by circulating anaerobic effluent through the tank and applying aeration for 72 h to facilitate biofilm formation and stabilisation. The EGSB-MBR and DEGBR-MBR units were operated at constant flow rates of 0.36 L/h and 0.38 L/h, respectively. The MBR was operated under ambient temperature (20–24 °C), with the membrane system functioning under a transmembrane pressure of – 0.4 bar.

2.5 Sampling and analytical procedures

Sampling was conducted every 48 h over the operational period from key system points, namely the raw PSW, post–pre-treatment, post-bioreactor, and post-MBR, as illustrated in Fig. 1b. The parameters analysed included chemical oxygen demand (COD), total suspended Solids (TSS), and fats, oils and grease (FOG). All analyses were carried out at the City of Cape Town Scientific Services Laboratory (South Africa) using APHA Standard Methods (21st Edition), with a summary provided in Table 4. Compliance was assessed against the City of Cape Town's Wastewater and Industrial Effluent By-law [8] discharge standards [7].

2.6 Statistical analysis

A paired two-tailed Student's t-test was applied to compare the removal efficiencies (COD, TSS, and FOG) between the EGSB and DEGBR reactors, and between the full treatment trains (Pre-treatment–EGSB–MBR vs. Pre-treatment–DEGBR–MBR). This approach was selected due to the paired design of the experiment, the normal distribution of data (confirmed via skewness and kurtosis), and the need to determine whether observed differences were statistically significant ($p < 0.05$). Additionally, Pearson correlation analysis was conducted to assess interdependencies between removal parameters. Descriptive statistics (mean, standard deviation, skewness, and kurtosis) and probability density function (PDF) analyses were also performed to characterise the distribution and variability of treatment performance data. All statistical analyses were performed using Python (version 3.12.0) with the NumPy, SciPy, and Pandas libraries, considering a significance level of $p < 0.05$.

3 Results and discussion

3.1 Effect of enzymatic pre-treatment on reactor performance

The application of the enzymatic Eco-Fush™ pre-treatment significantly enhanced the anaerobic digestibility of the PSW. Initial concentrations of COD, FOG, and TSS in raw PSW were well above discharge limits, ranging from 6500 to 21,000 mg/L for COD, 640 to 4500 mg/L for FOG, and 2985–8363 mg/L for TSS. Pre-treatment analysis revealed substantial reductions up to 80% in FOG, and 56% and 38% in COD and TSS, respectively. These findings demonstrate superior performance over conventional methods such as thermal autoclaving, dissolved air flotation (DAF), and hydrodynamic cavitation, which typically achieve FOG reductions of 63% [22], 61–67% [11], and up to 71% [18], respectively (Fig. 2).

The improved removal efficiency is attributed to the enzymatic delipidation action of Eco-Flush™, which enhances hydrolysis and reduces fat-induced interference in downstream anaerobic digestion. Damasceno et al. [9] highlighted the adverse effects of high lipid content on anaerobic digestion, particularly in PSW, where FOG bind to consortia's sludge granules, limiting biodegradability and promoting sludge washout. Similar challenges have been documented in EGSB systems by Basitere et al. [4]. This study

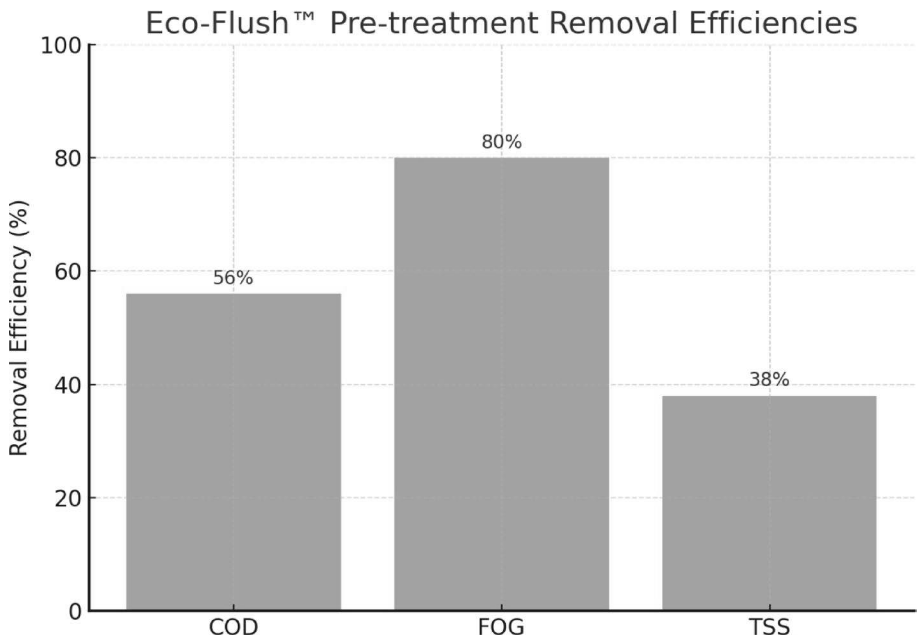

Fig. 2 Removal efficiencies of COD, FOG, and TSS from poultry slaughterhouse wastewater after enzymatic Eco-Flush™ pre-treatment

Fig. 3 **a** Aerobic pre-treatment of Eco-Flush™ enzymes and poultry slaughterhouse wastewater (PSW); **b** Filtration of feathers and suspended solids from PSW during the pre-treatment process

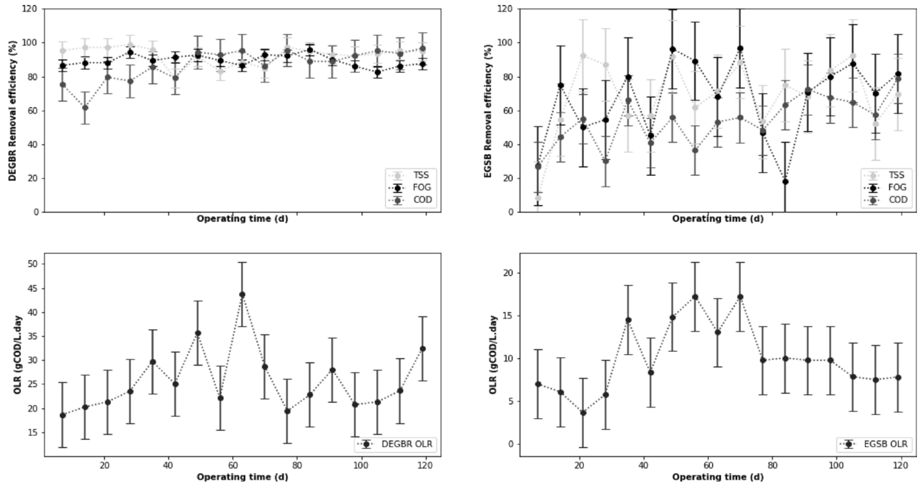

Fig. 4 COD, TSS, and FOG removal efficiencies for the DEGBR (left) and EGSB (right) reactors under varying organic loading rate (OLR) conditions. The top panels show removal efficiencies, and the bottom panels show corresponding OLR fluctuations. The x-axis represents operating time, which is common to both the removal efficiency and OLR plots to enable direct comparison

effectively mitigated such operational issues, including clogging and the need for frequent backwashing, as visually represented in Fig. 3a and b.

3.2 Organic loading rates and impact on reactor stability

Given the complex nature of PSW, initial reactor start-up often requires dilution to mitigate reactor shock caused by high OLRs, as observed by Njoya et al. [32]. It is emphasised that managing fluctuations in OLR, particularly those related to COD concentrations, is critical for maintaining stable reactor performance. Figure 4 highlights the variability in OLR throughout the study period, with the DEGBR operating under a higher range (18–44 g COD/L·day) compared to the EGSB (4–18 g COD/L·day). The corresponding average HRTs were approximately 5.4 h for the DEGBR and 18 h for the EGSB.

The DEGBR maintained consistently high removal efficiencies—COD (82–89%), TSS (90–95%), and FOG (85–92%)—despite the dynamic loading conditions. In contrast, the EGSB exhibited more erratic removal patterns, particularly for COD (45–60%) and FOG (55–70%), with TSS performance remaining relatively lower and less stable. This is further supported by the narrower variability observed in the DEGBR results, as

Table 5 Statistical comparison of DEGBR and EGSB performance for COD, TSS, and FOG

Parameter	Degrees of Freedom	t-Stat	t-Critical (two-tail)	*P*-value (two-tail)
COD	16	10.936	2.120	7.8×10^{-9}
TSS	16	4.442	2.120	4.1×10^{-4}
FOG	16	3.794	2.120	1.6×10^{-3}

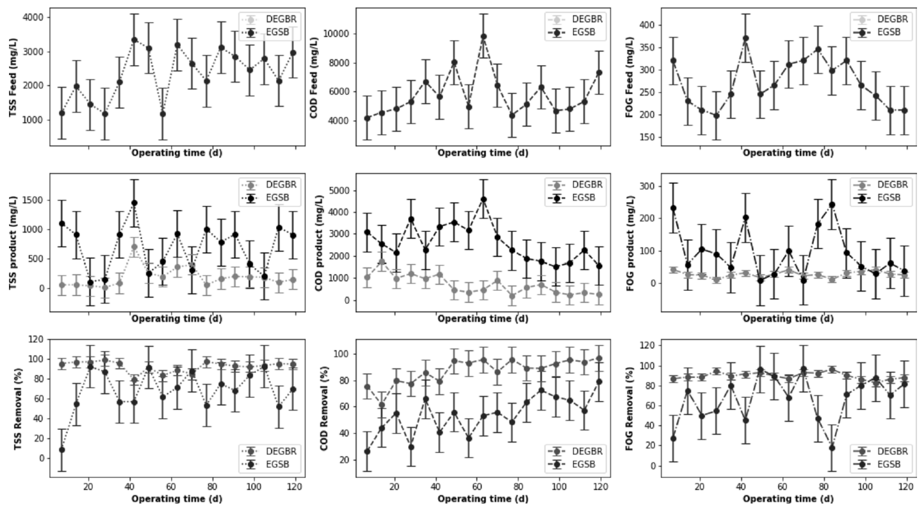

Fig. 5 Influent (feed) concentrations of COD, TSS, and FOG and corresponding removal efficiencies in the DEGBR reactor over the same operating days. Error bars represent standard deviations. The x-axis represents operating time, aligned for both feed and removal data to allow direct comparison

shown in Fig. 4, and confirmed by the probability density function (PDF) analysis (Fig. 6) and paired t-test results (Table 5), which indicated statistically significant differences ($p < 0.05$) in COD, TSS, and FOG removal between the two systems. These findings suggest that the DEGBR's design offers enhanced resilience and process stability under fluctuating influent conditions.

The up-flow configuration of the EGSB may have contributed to operational challenges such as sludge washout and short-circuiting under variable loading, consistent with findings by Basitere et al. [4]. In contrast, the downflow hydrodynamics and controlled recirculation of the DEGBR enhanced sludge–substrate contact and improved gas disengagement, reducing dead zones and maintaining bed integrity. These design advantages likely account for its superior and more consistent performance even under shock loading conditions. While both reactors demonstrated the capacity to treat high-strength PSW, the DEGBR showed greater adaptability and consistent performance, making it more suitable for decentralised applications that encounter variable and shock-prone loading regimes.

3.3 Performance comparison between EGSB and DEGBR reactors

Figure 5 illustrates the time-based performance of the DEGBR and EGSB in treating pre-treated PSW. Although both systems received feed of identical quality, the DEGBR consistently achieved higher and more stable COD, TSS, and FOG removals. Visual inspection of the plots shows that the DEGBR maintained elevated and steady removal trends, whereas the EGSB exhibited greater variability and frequent drops in performance, particularly for COD and FOG. This superior performance can be attributed to the DEGBR's hydrodynamic and mass-transfer advantages. The down-flow configuration with controlled recirculation enhances sludge–substrate contact, maintains uniform bed expansion, and facilitates gas disengagement, preventing dead zones and preserving bed integrity. These conditions promote sustained biofilm activity and longer biomass–influent contact time, resulting in improved degradation even under fluctuating OLRs. By contrast, the EGSB's up-flow configuration is more prone to sludge washout and short-circuiting during load shocks, leading to less stable performance. The DEGBR's narrower probability distribution functions (Fig. 6) and reduced variability further confirm its resilience, highlighting its potential as a robust solution for high-strength, FOG-rich PSW, especially in decentralised settings where influent variability is common.It is worth noting that the final effluents from both reactors, with and without MBR polishing, complied with the City of Cape Town Wastewater and Industrial Effluent By-law [8] discharge standards for COD, TSS, and FOG, thereby confirming the suitability of both treatment systems for direct discharge or further reuse applications.

Probability distribution functions (Fig. 6) provide further insight, showing that the DEGBR achieved higher mean removal efficiencies—COD (87%), FOG (89%), and TSS (92%)—with narrower standard deviations. In contrast, the EGSB attained lower mean values of 54% (COD), 67% (FOG), and 68% (TSS), along with wider variability. The tighter distribution curves for the DEGBR suggest greater process consistency and operational reliability. Skewness and kurtosis values indicate more symmetrical and sharper distributions for DEGBR performance, reflecting its stable operation under PSW conditions.

Correlation analyses (Fig. 7a and b) further revealed weak inter-parameter relationships for both reactors. Pearson correlation coefficients and associated p-values indicated no statistically significant correlations between COD, TSS, and FOG removal. This reinforces the idea that each pollutant's removal efficiency was independently influenced by the reactor configuration and its resilience to operational variability.

To statistically validate these observed differences, paired t-tests (Table 5) were performed for each parameter. Results showed t-statistics significantly exceeding the critical value (2.120), and p-values well below 0.05 for all parameters, confirming that the DEGBR's superior performance was statistically significant and not due to random variation.

In summary, the combination of time-series trends, statistical distributions, and correlation analysis affirms the DEGBR's robustness and efficiency in treating high-strength FOG-rich wastewater such as PSW, outperforming the EGSB in both consistency and magnitude of contaminant removal. Probability distribution functions (PDFs) presented in Fig. 6 further reinforce these observations, showing near-normal distributions with higher mean removal efficiencies and lower standard deviations in the DEGBR. Although correlation analysis (Fig. 7a and b) indicated weak interdependencies among COD, TSS, and FOG removal rates, this suggests the systems' performance is robust across parameters and not overly dependent on a single pollutant's behaviour.

3.4 Performance comparison of pre-treatment–DEGBR–MBR and pre-treatment–EGSB–MBR treatment trains

The overall treatment performance of two integrated systems, i.e.,Pre-treatment–DEGBR–MBR and Pre-treatment–EGSB–MBR was evaluated for poultry slaughterhouse wastewater (PSW). Both configurations included a common pre-treatment step followed by either the DEGBR or EGSB reactor and concluded with MBR as the

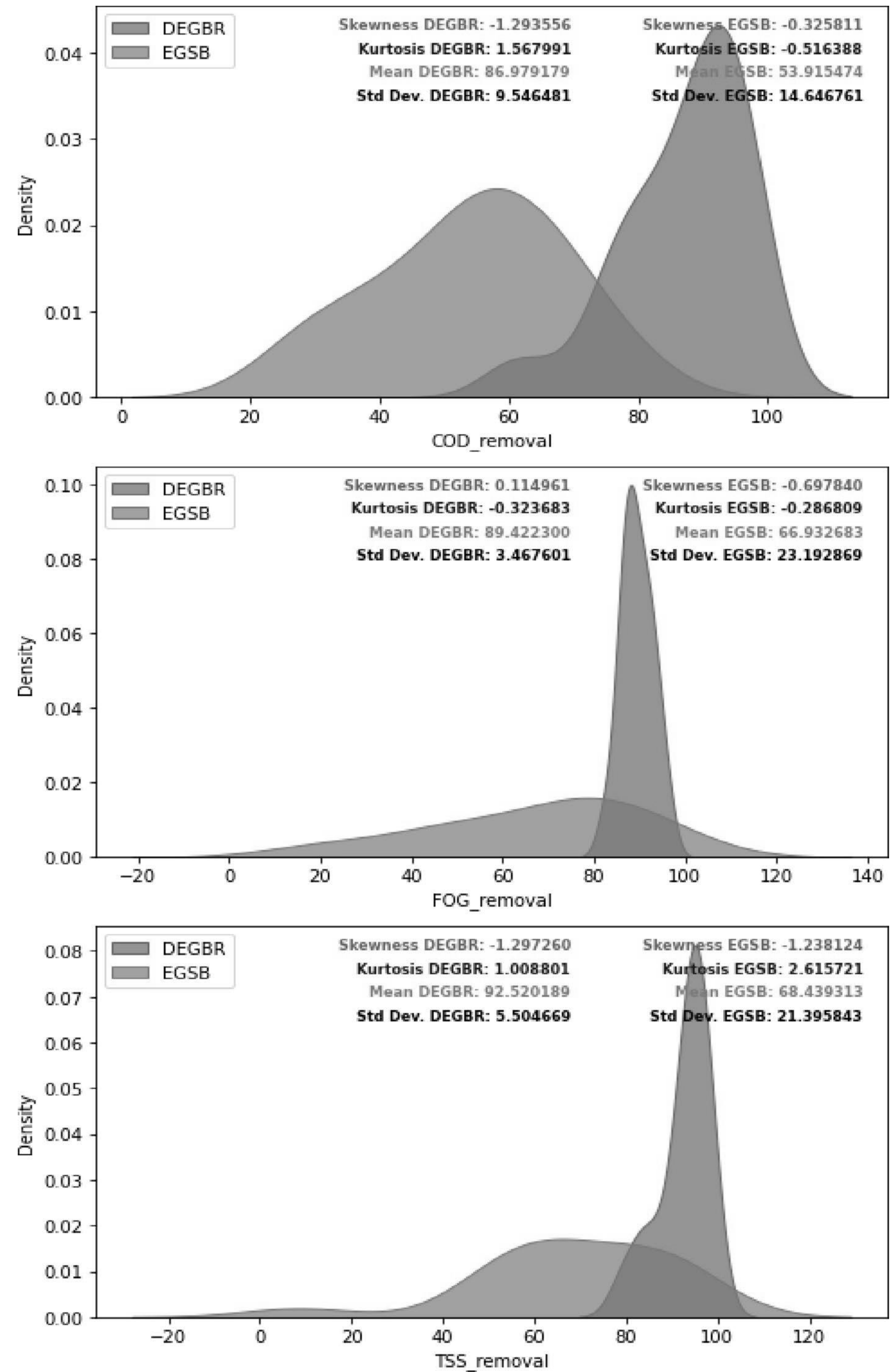

Fig. 6 Probability density functions of the removal efficiencies in the DEGBR and EGSB

post-treatment stage. The temporal performance data for COD, TSS, and FOG are presented in Fig. 8.

The results indicate that while both systems achieved high removal efficiencies exceeding 95% throughout the operational period, the DEGBR-based system consistently outperformed the EGSB-based configuration. This superior performance was particularly evident in the removal of COD and FOG, which are often more challenging due to their

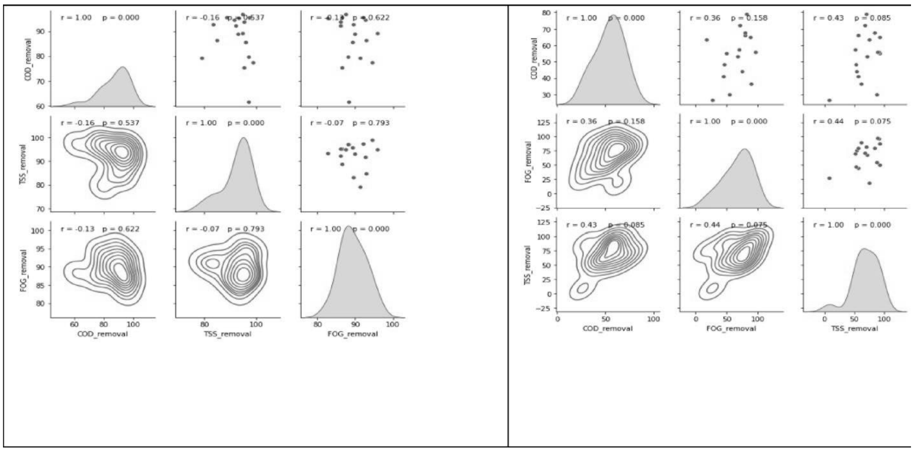

Fig. 7 **a** and **b** Correlation analysis between the removal efficiencies of the DEGBR and EGSB

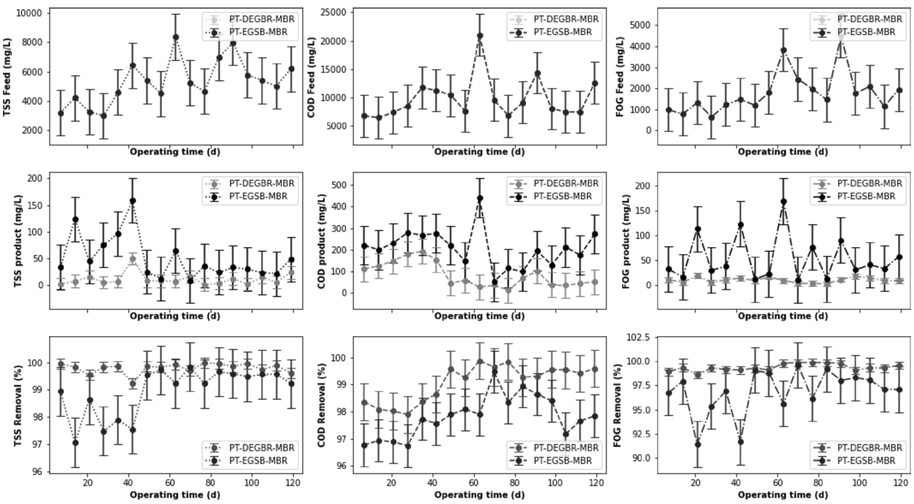

Fig. 8 Comparative time-based performance of the integrated treatment systems comprising Pre-treatment–DEGBR–MBR and Pre-treatment–EGSB–MBR for COD, TSS, and FOG removal. Error bars represent standard deviations. The x-axis represents operating days, which are common across all panels, allowing direct comparison of performance trends between the two treatment trains

association with FOG-rich wastewaters. Notably, the MBR post-treatment contributed significantly to polishing the effluent quality in both configurations, especially enhancing the performance of the EGSB train.

Figure 9 presents the probability density functions (PDFs) for COD, TSS, and FOG removal in the PT-DEGBR–MBR and PT-EGSB–MBR systems, along with associated descriptive statistics. The DEGBR-based system consistently exhibited higher mean removal efficiencies of 99.07% (COD), 99.35% (TSS), and 99.80% (FOG) compared to the EGSB system's 97.82%, 96.87%, and 98.95%, respectively. Moreover, the DEGBR distributions were more compact with lower standard deviations and negatively skewed profiles, indicating consistent and reliable performance. In contrast, the EGSB system showed greater variability and right-skewed or flattened distributions, particularly for TSS and FOG, with elevated standard deviations and lower kurtosis. These differences underscore the superior operational stability and treatment effectiveness of the DEGBR–MBR configuration, especially under high-strength, FOG-rich wastewater conditions.

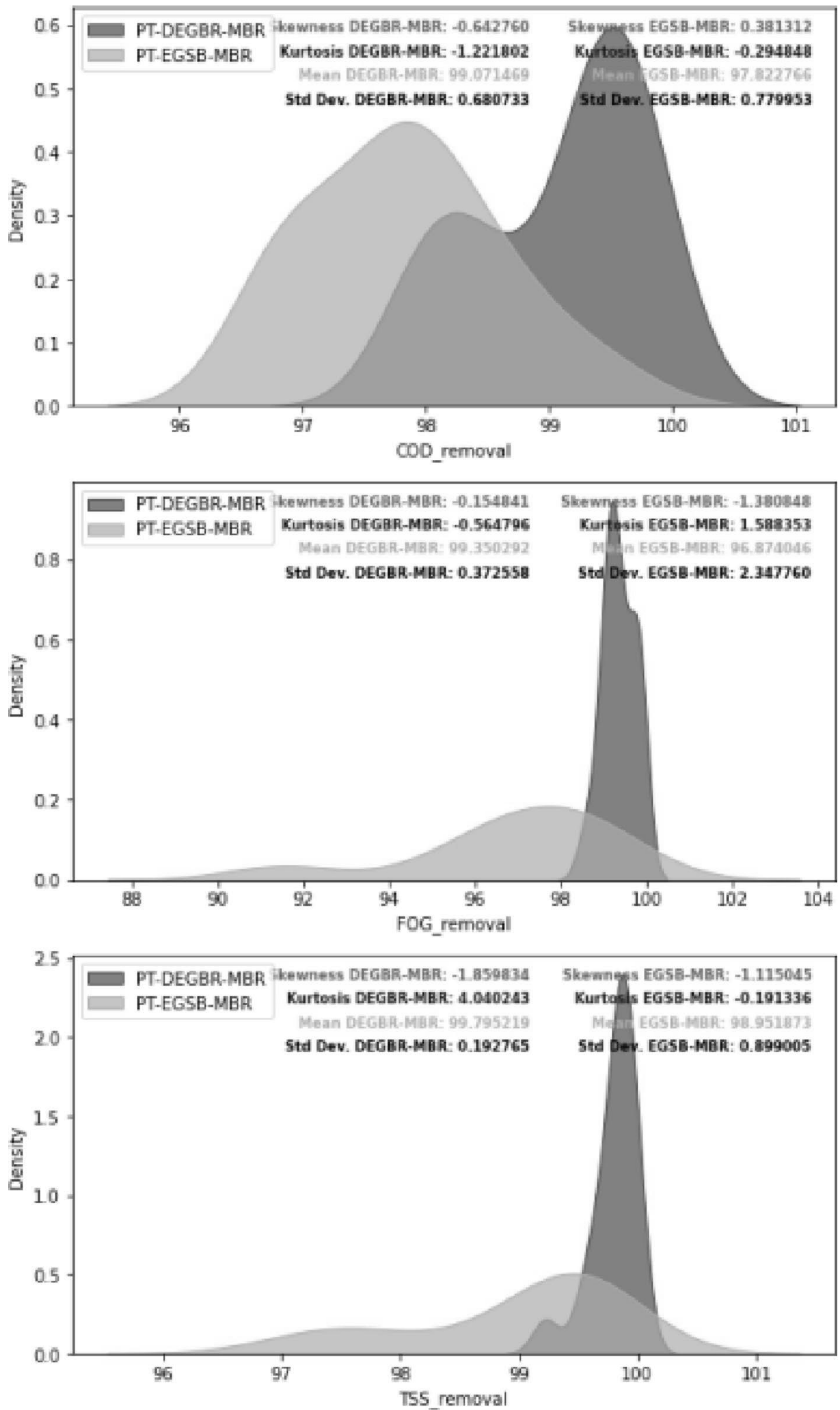

Fig. 9 Probability density function (PDF) comparisons for individual bioreactors (DEGBR vs. EGSB, left column) and integrated systems (PT-DEGBR–MBR vs. PT-EGSB–MBR, right column) showing removal efficiencies for COD (top), FOG (middle), and TSS (bottom)

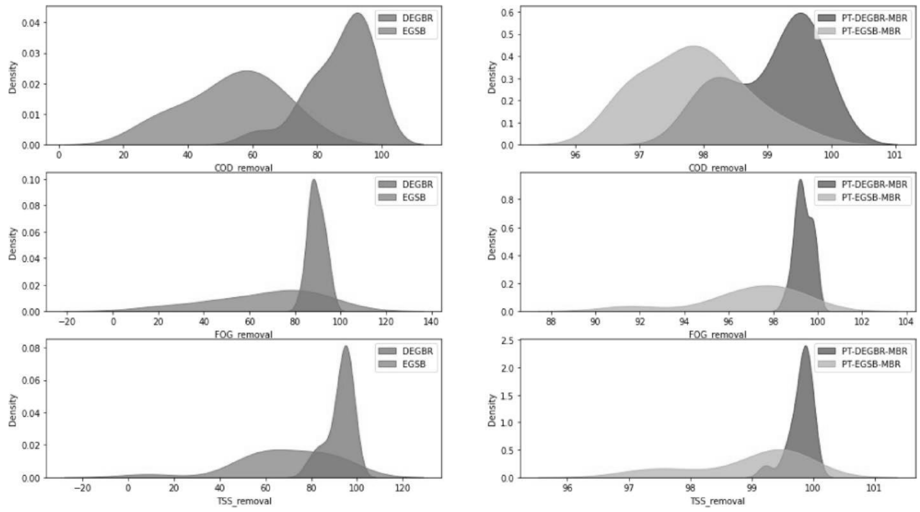

Fig. 10 Comparison of probability density functions (PDFs) for individual bioreactors (DEGBR vs. EGSB, left column) and integrated treatment systems (PT-DEGBR–MBR vs. PT-EGSB–MBR, right column) for COD (top), FOG (middle), and TSS (bottom) removal

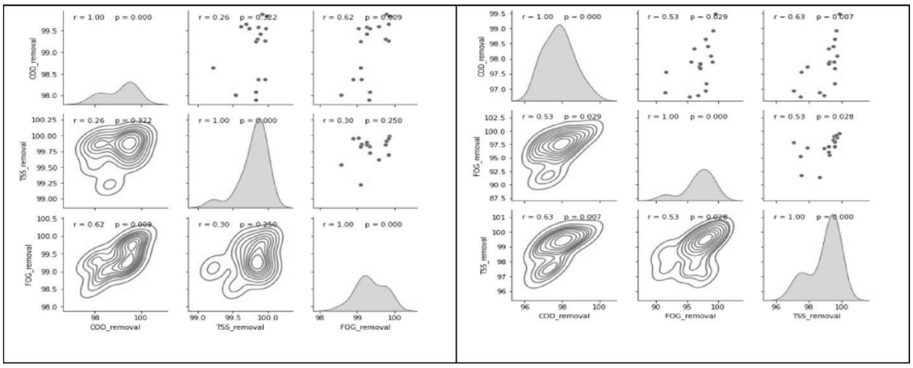

Fig. 11 **a** Pearson correlation and kernel density contour plots for COD, TSS, and FOG removal efficiencies in the PT-DEGBR–MBR system(left). **b** Corresponding plots for the PT-EGSB–MBR system(right)

Figure 10 illustrates that the DEGBR reactor outperforms the EGSB in both standalone and integrated configurations, showing higher and more consistent removal efficiencies for COD, TSS, and FOG. The DEGBR's narrower, right-skewed distributions indicate stable performance, likely due to better sludge retention and reduced sludge washout. While the addition of the MBR improved both systems, the PT-DEGBR–MBR train maintained superior efficiency with reduced variability. In contrast, the PT-EGSB–MBR system exhibited broader distributions, highlighting its greater sensitivity to influent variability. The findings highlight the operational stability and effectiveness of the PT-DEGBR–MBR configuration, particularly in handling FOG-rich, high-strength wastewaters.

Figure 11a and b present Pearson correlation analyses between COD, TSS, and FOG removal efficiencies for the PT-DEGBR–MBR and PT-EGSB–MBR systems, respectively. In the PT-DEGBR–MBR configuration (Fig. 11a), only one statistically significant correlation was observed between COD and FOG ($r = 0.62$, $p = 0.009$) while the other relationships were weak and not significant ($p > 0.05$), indicating largely independent and stable removal pathways. In contrast, the PT-EGSB–MBR system (Fig. 11b) displayed

Table 6 Statistical comparison of removal efficiencies between PT-DEGBR–MBR and PT-EGSB–MBR systems

Parameter	Degree of Freedom	t Stat	$P(T \le t)$ one-tail	t Critical one-tail	$P(T \le t)$ two-tail	t Critical two-tail
COD	16	8.86	7.0×10^{-8}	1.75	1.4×10^{-7}	2.12
TSS	16	4.09	0.00043	1.75	0.00086	2.12
FOG	16	4.64	0.00013	1.75	0.00027	2.12

significant positive correlations among all parameter pairs: COD and TSS ($r = 0.61$, $p = 0.017$), COD and FOG ($r = 0.53$, $p = 0.029$), and TSS and FOG ($r = 0.51$, $p = 0.029$). This suggests more interdependent removal behaviour in the PT-EGSB-based system, potentially due to greater variability and sensitivity to influent fluctuations. The correlation analysis underscores the consistent performance of the PT_DEGBR–MBR system, reinforcing its suitability for treating high-strength wastewater with variable influent characteristics.

To further validate these differences, an independent t-test was performed to compare the mean removal efficiencies of both systems. As shown in Table 6, the t-statistic values for COD (8.86), TSS (4.09), and FOG (4.64) all exceeded the critical t-values for both one-tail (1.75) and two-tail (2.12) tests, with corresponding *p*-values well below the 0.05 significance threshold. These results confirm that the PT-DEGBR–MBR system achieved statistically superior performance compared to the PT-EGSB–MBR system across all evaluated parameters.

4 Conclusion and recommendations

This study demonstrated the comparative effectiveness of the (DEGBR and EGSB reactor for the treatment of high-strength PSW, both as standalone systems and as part of integrated treatment trains incorporating enzymatic pre-treatment and MBR polishing. The DEGBR consistently outperformed the EGSB in terms of COD, TSS, and FOG removal, achieving removal efficiencies exceeding 99% in the integrated configuration. Time-based trends, probability density functions, and statistical analysis confirmed the DEGBR's superior performance, marked by higher stability, lower variability, and resilience to organic loading fluctuations. In contrast, the EGSB exhibited greater sensitivity to influent variability and operational challenges, including sludge washout, particularly under FOG-rich conditions. Correlation analysis further reinforced these findings, with the DEGBR showing largely independent removal dynamics, while the EGSB system revealed interdependent performance characteristics.

The PT-DEGBR–MBR treatment train therefore offers a robust, efficient, and scalable solution for decentralised treatment of lipid-rich industrial effluents such as those from poultry processing facilities. While this investigation focused on PSW, the promising results suggest that the DEGBR system could be extended to other high-strength wastewaters, including dairy effluents, food and beverage industry wastewaters, and agro-industrial effluents containing elevated levels FOG concentration, and suspended solids. Future research should investigate the performance of DEGBR-based systems under diverse wastewater compositions, variable climatic conditions, and long-term operational settings. In addition, further studies examining sludge characteristics, biogas production potential, membrane fouling behaviour, and the integration of automation and process control would support broader adoption and optimisation of this treatment approach across different industrial sectors.

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Author contributions
Phumeza A. Dyosile: Conducted the experiments, collected and analyzed the data, and prepared the initial draft of the manuscript as part of her Master's research. Mahomet Njoya: Contributed to study conceptualization, assisted with data interpretation, and performed the statistical analyses. Seteno K.O. Ntwampe: Served as co-supervisor; contributed to the conceptual framework and provided critical revisions and editorial guidance throughout the manuscript development. Timothy G. Ellis: Contributed to the conceptual development of the modified DEGBR reactor based on the original SGBR design, and provided technical insights and critical review of the manuscript. Moses Basitere: Principal supervisor of the project; led the conceptualization, experimental design, and project coordination. Oversaw data interpretation, manuscript review, and provided strategic direction. Secured research funding and ensured overall project execution.

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Data availability
The data that support the findings of this study are available from the corresponding author upon request.

Declarations

Ethics approval
The authors declare that this study did not involve any human participants or animals. However, ethical approval to conduct the research was obtained from the Cape Peninsula University of Technology as part of the postgraduate research proposal review and approval process.

Consent to participate
Not applicable, as this study did not involve human participants.

Consent to publish
Not applicable, as this manuscript does not include any individual person's data, images, or identifiable information.

Competing interests
Moses Basitere reports financial support, including article processing charges and provision of equipment or research materials, from the National Research Foundation. All other authors declare that they have no known financial or non-financial competing interests, such as personal relationships, institutional affiliations, or intellectual beliefs, that could have appeared to influence the work reported in this paper.

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