Sustainable Chemistry One World 10 (2026) 100213

Contents lists available at ScienceDirect

Sustainable Chemistry One World

journal homepage: www.sciencedirect.com/journal/sustainable-chemistry-one-world

Smart solar water treatment: Sensor-informed control of solar TiO_2 photocatalysis for sustainable environmental water treatment

Lukman O. Kolawole[a], Sandra C. Akaelu[b], Stephanie O. Akaelu[c,d], Chijioke C. Chuwa[e], Ifeoluwa E. Elemure[f], Adeyinka G. Ologun[g,h,*], Abiodun F. Ibidunmoye[i], Francis T. Omigbodun[j]

[a] *Department of Data Science, Middlesex University London, The Burroughs, Hendon, London NW4 4BT, UK*
[b] *Business administration (MBA) University of Sunderland, Sunderland, UK*
[c] *Microbiology Department, University of Lagos, Lagos, Nigeria*
[d] *International Business Management Department, Northumbria University, Newcastle, UK*
[e] *Department of Mechanical and Construction Engineering, Northumbria University, Newcastle upon Tyne NE1 8ST, United Kingdom*
[f] *School of Mechanical and Design Engineering, University of Portsmouth, Portsmouth PO1 3DJ, UK*
[g] *Faculty of Business and Media, Selinus University of Sciences and Literature, Italy*
[h] *Department of Business School, University of Wolverhampton, Business School, England, UK*
[i] *Department of Economics and Criminology, University of Lagos, Nigeria*
[j] *Wolfson School of Mechanical, Electrical and Manufacturing Engineering, Loughborough University, LE 11 3TU, UK*

ARTICLE INFO

Keywords:
Smart environmental management
Solar-responsive control
Data-driven water treatment
Photocatalytic reactor optimisation
Circular water systems
Environmental decision-support modelling

ABSTRACT

This study presents a solar-driven photocatalytic treatment system for decentralised water remediation evaluated under real outdoor conditions. *A* TiO_2-based photocatalyst operated in a 5 L compound parabolic collector (CPC) reactor was assessed using a combination of field Analytical modelation and irradiance–performance analysis. Real-time global horizontal irradiance (260–910 W m^{-2}) showed a strong linear relationship with apparent degradation kinetics ($R^2 = 0.84$–0.88), demonstrating that photocatalytic activity was primarily governed by photon availability under natural sunlight. Under peak solar conditions, removals of 92 ± 4% atrazine, 86 ± 6% imidacloprid, and 79 ± 5% sulfamethoxazole were achieved within 60 min. To examine operational optimisation, treatment performance was analysed against concurrent irradiance data to identify efficient operating windows. Based on this relationship, an irradiance-gated operational strategy was estimated to increase daily pollutant throughput by approximately 32% compared with fixed-schedule operation. Analytical models using natural river water showed a 20–35% decrease in removal efficiency, attributed to increased turbidity and dissolved organic matter that attenuate light penetration and compete for reactive species. Overall, the results demonstrate the feasibility of solar CPC photocatalysis for decentralised treatment of agricultural runoff and highlight the importance of irradiance-responsive operation for improving process efficiency under variable sunlight.

1. Introduction

The growing pressures of population expansion and industrialised agriculture have intensified the release of emerging pollutants (EPs) such as herbicides, neonicotinoids, and veterinary pharmaceuticals into surface and subsurface waters [1,2]. These persistent compounds, often present at trace concentrations, pose cumulative risks to aquatic ecosystems, food safety, and rural livelihoods [3,4]. The problem is particularly acute in agricultural supply chains where runoff from fertilised fields and livestock operations transports contaminants downstream, closing a pollution loop that undermines water reuse and sustainable production [5,6]. Conventional wastewater treatment facilities are typically centralised, energy-intensive, and inaccessible to smallholder or decentralised farms, highlighting the need for localised,

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* Corresponding author at: Faculty of Business and Media, Selinus University of Sciences and Literature, Italy.
E-mail addresses: o_lukuman@yahoo.com (L.O. Kolawole), akaelusandra@gmail.com (S.C. Akaelu), Steph_chukwudum@yahoo.com (S.O. Akaelu), chrischuwa25@gmail.com (C.C. Chuwa), elemure06@gmail.com (I.E. Elemure), adeyinkaologun14@gmail.com (A.G. Ologun), ibidunmoyefemi@gmail.com (A.F. Ibidunmoye), Omigboduntobi@gmail.com (F.T. Omigbodun).

https://doi.org/10.1016/j.scowo.2026.100213
Received 12 February 2026; Received in revised form 15 March 2026; Accepted 17 March 2026
Available online 18 March 2026

low-energy remediation technologies integrated into the operational fabric of agricultural enterprises [7,8].

From a sustainability and circular-economy perspective, addressing water contamination within the agricultural value chain is essential for achieving resource efficiency and environmental resilience. Clean water is not only a natural capital but also a strategic input influencing crop yields, supply reliability, and compliance with environmental regulations [9,10]. Sustainable enterprise operation now extends beyond product-level eco-efficiency to include waste minimisation, carbon reduction, and the circular use of process water within agricultural production systems [11,12]. The transition to closed-loop water management therefore requires affordable treatment systems capable of removing pollutants at the point of generation before runoff enters shared waterways or irrigation canals [13,14].

Among various advanced oxidation processes (AOPs), heterogeneous photocatalysis offers a technically simple pathway for decentralised water purification. It uses light energy to activate semiconductor catalysts such as titanium dioxide (TiO_2), producing reactive oxygen species (ROS) that oxidise a wide spectrum of organic pollutants [15,16]. TiO_2 remains the most extensively studied photocatalyst because it is abundant, photostable, and non-toxic [17,18].

However, most reported studies rely on artificial UV sources that deliver constant, high-intensity irradiation under laboratory conditions [19,20]. These controlled experimental environments do not capture the variability of natural sunlight, including diurnal cycles, spectral shifts, and intermittent cloud cover, which strongly influence photocatalytic performance under real environmental conditions [21,22].

Solar-driven photocatalysis has attracted increasing attention as a sustainable water treatment technology because it enables pollutant degradation using natural sunlight as the primary energy source. Extensive research has demonstrated that solar photocatalytic systems can effectively degrade a wide range of micropollutants in water while reducing external energy requirements. Several comprehensive reviews have documented the development of solar advanced oxidation processes (solar-AOPs) and their application to environmental remediation. [Malato et al., Catalysis Today 2009; Malato et al., Applied Catalysis B 2002]

Consequently, although the fundamental relationship between irradiance and photocatalytic reaction kinetics has been widely reported in laboratory studies, fewer investigations have examined how these relationships translate into operational performance under natural solar variability.

Photocatalytic degradation of organic pollutants on semiconductor surfaces is commonly described using the Langmuir–Hinshelwood kinetic model, where reaction rates depend on pollutant adsorption and photon-induced radical generation. Under dilute pollutant concentrations, this mechanism can often be simplified to pseudo-first-order kinetics, allowing apparent reaction rate constants (k_{app}) to be used as practical indicators of photocatalytic activity. [Herrmann, Catalysis Today 1999]

Solar-driven photocatalysis therefore represents a promising approach for sustainable water treatment, particularly when integrated into decentralised environmental management systems. By utilising sunlight as the primary energy input, solar photocatalytic processes can reduce dependence on external electricity sources while minimising chemical consumption [23–25].

Recent studies have explored the design and optimisation of photocatalytic materials, reactor configurations, and solar reactors for the degradation of pollutants in water systems. Previous studies have demonstrated that reactor geometry, catalyst distribution, and photon flux strongly influence photocatalytic degradation kinetics and solar reactor performance [26–28].

Recent research has focused on improving the efficiency of solar photocatalytic systems through both material development and reactor engineering. Studies on TiO_2-based photocatalysts have shown that modifications in catalyst morphology, surface properties, and light absorption characteristics can enhance pollutant degradation under solar irradiation [26–28]. In parallel, advances in reactor design and modelling have improved photon distribution and mass transfer within solar photocatalytic reactors, enabling more efficient utilisation of natural sunlight [20,21]. While many of these investigations emphasise catalyst development or laboratory-scale optimisation, fewer studies have examined the operational behaviour of solar photocatalytic reactors under real outdoor conditions. The present study therefore focuses on the performance of a practical compound parabolic collector (CPC) reactor operated under natural sunlight, with particular attention to the relationship between solar irradiance variability and photocatalytic degradation kinetics. [Santana & Rivas, Chemical Engineering Journal 2021].

Despite these advances, practical deployment in agricultural settings remains limited because many systems are tested only under controlled laboratory conditions rather than real outdoor environments.

Compound parabolic collector (CPC) reactors have emerged as effective designs for solar photocatalysis because they concentrate both direct and diffuse sunlight onto tubular reaction zones while maintaining moderate operating temperatures [29,30]. Their optical geometry enhances photon capture even under variable cloud conditions, making them suitable for temperate regions with moderate solar irradiance [31, 32].

The performance of CPC reactors for solar photocatalysis has been extensively investigated, demonstrating their ability to maintain efficient pollutant degradation under fluctuating solar conditions. [Fresno et al., Solar Energy 2018]

Nevertheless, quantitative studies linking real-time solar irradiance to photocatalytic degradation rates in outdoor CPC systems remain relatively limited, particularly for agricultural runoff treatment. Field investigations have shown that solar irradiance variability can significantly influence photocatalytic reaction rates and treatment efficiency in outdoor systems, highlighting the importance of real-time solar monitoring. [Byrne & Dunlop, Chemical Engineering Journal 2023]

This study, therefore, investigates the performance of a solar-driven TiO_2-based photocatalytic system operated in a compound parabolic collector (CPC) reactor under natural outdoor conditions. Rather than proposing a fundamentally new photocatalytic mechanism, the work focuses on evaluating how solar irradiance variability influences pollutant degradation kinetics and treatment capacity in a decentralised water treatment context. The research combines numerical modelling and field Analytical modelation to examine reactor performance under fluctuating sunlight conditions. Specifically, the objectives are to (i) simulate photon absorption and degradation kinetics under variable irradiance conditions, (ii) validate the model through outdoor Analytical models conducted in Wolverhampton, UK (52.586° N, −2.128° W), (iii) examine the relationship between global horizontal irradiance (GHI) and apparent reaction rate constants (k_{app}), and (iv) evaluate an irradiance-responsive operational strategy for improving treatment throughput.

The contribution of this work lies in providing field-based analytical model evidence linking solar irradiance variability to photocatalytic degradation performance in a CPC reactor treating contaminants in agricultural runoff. By integrating solar monitoring with reactor operation, the study demonstrates how solar-driven treatment systems may be operated more efficiently under realistic environmental conditions. These findings contribute to the development of practical solar photocatalytic water treatment systems for decentralised agricultural applications while highlighting the importance of environmental variability in reactor design and operation (Fig. 1).

2. Methodology

An analytical model was conducted outdoors on the City Campus roof (52.586° N, −2.128° W; elevation 163 m) between 15 June and 15 August 2025. Meteorological parameters (air temperature and wind

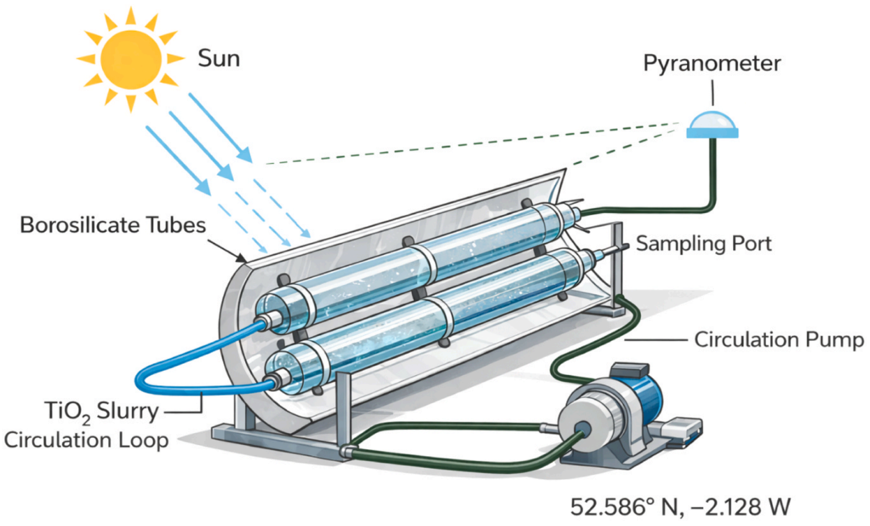

Fig. 1. Schematic diagram of the 5 L CPC solar reactor.

speed) were recorded using a nearby weather station. Global horizontal irradiance (GHI) was measured at 1-minute intervals using an ISO First Class pyranometer (285–3000 nm), calibrated in April 2025. The sensor was positioned adjacent to the reactor and logged continuously to capture real sunlight variability, including clear and cloud-affected periods representative of practical operation. A cosine-corrected photodiode placed near the reactor tubes was used to verify short-term irradiance fluctuations during each run.

2.1. Reactor configuration and catalyst

Photocatalytic Analytical models were performed in a recirculating compound parabolic collector (CPC) slurry reactor comprising borosilicate glass tubes, with a working volume of 5 L and an illuminated area of 0.48 m^2. The CPC reflector frame was oriented south at a 30° inclination. The reaction mixture was circulated using a peristaltic pump at 1.5 L min^{-1} (Re ≈ 2100) to maintain suspension of catalyst particles. Degassing ports were included to minimise bubble accumulation in the tubes [33,34].

Titanium dioxide P25 (Evonik) was used as the photocatalyst at a concentration of 0.5 g L^{-1} . The catalyst was used in its commercial form without polymer modification or surface treatment. Before each Analytical model, suspensions were sonicated for 10 min to ensure uniform dispersion. Reactor temperature increased naturally from approximately 21–32 °C during the analytical models, and no external cooling was applied to maintain realistic outdoor conditions.

2.2. Water matrices and target pollutants

Two matrices were investigated. A synthetic agricultural runoff solution contained $NaNO_3$ (20 mg N L^{-1}), KH_2PO_4 (2 mg P L^{-1}), humic acid (5 mg L^{-1} DOC), and Ca^{2+}/Mg^{2+} salts corresponding to hardness levels of 2.5 and 1.0 mmol L^{-1} (pH 7.6). Real surface water samples were collected from the River Tame (52.514° N, −1.938° W) and screened through a 100 μm mesh to remove coarse particles.

Atrazine, imidacloprid, and sulfamethoxazole were used as model pollutants at 100 μg L^{-1} each. In river water Analytical models, compounds were spiked to the same concentration for comparability. Before illumination, the suspension was stirred in the dark for 30 min to establish adsorption equilibrium.

2.3. Analytical Model operation

To capture diurnal solar variability, Analytical models were conducted during three time periods: morning (08:00–10:00 BST), midday (11:30–13:30), and afternoon (15:00–17:00). Each run consisted of 60 min of illumination with sampling at 10-minute intervals. *Short cloud*-induced irradiance changes were recorded through the irradiance logging system and incorporated into the kinetic analysis.

2.3.1. Analytical measurements

Pollutant concentrations were measured using HPLC-DAD with a C18 column and a water/acetonitrile gradient containing 0.1% formic acid. Detection limits ranged from 0.5 to 1 μg L^{-1} . Dissolved organic carbon (DOC) and UV_{254} were measured to track bulk organic changes. Turbidity and zeta potential were monitored to assess the effects of the matrix on catalyst stability. Titanium leaching was analysed by ICP-OES and remained below the detection limit [35,36].

Toxicity changes in treated effluents were evaluated using the *Aliivibrio fischeri* bioluminescence inhibition test (15-minute exposure).

2.3.2. Control analysis and catalyst recovery

Control Analytical models included dark adsorption runs, solar irradiation without a catalyst, and radical-scavenging tests using sodium azide (10 mM). To evaluate catalyst reuse, the slurry was allowed to settle for approximately 45 min after each Analytical model. The clarified supernatant was decanted, and the recovered catalyst was rinsed once with deionised water before reuse. Reusability was assessed over five consecutive cycles (60 min illumination per cycle).

2.4. Kinetic analysis

Pollutant degradation was described using apparent first-order kinetics:

$$-\ln\left(\frac{C}{C_0}\right) = k_{app}t$$

where $k_{app}$is the apparent reaction rate constant. Rate constants were obtained from linear regression of concentration data over the 0–60-minute period. Relationships between $\mathbf{k_{app}}$and the mean irradiance recorded during each run was examined using linear regression models. All Analytical models were conducted in triplicate, and uncertainties are reported as 95% confidence intervals.

Additional details on reactor hydraulics and the analytical model setup are provided in the Supplementary Information.

3. Results

3.1. *Solar Irradiance Landscape*

During the 24-day analytical model campaign, solar exposure varied substantially in response to typical summer weather fluctuations. The mean global horizontal irradiance (GHI) recorded during operational runs ranged from 260 to 910 W m^{-2}, with a median value of approximately 640 W m^{-2}. This range reflected alternating clear and partly cloudy conditions common in mid-latitude summers. Noon sessions consistently exhibited the highest photon flux and the lowest temporal variability, with mean irradiance levels approximately 210 ± 60 W m^{-2} higher than morning measurements. Quantitatively, the coefficient of variation (CV) for noon intervals averaged 0.17 compared with 0.29 during morning tests, indicating that midday conditions provided the most stable illumination for photocatalytic operation.

Late-afternoon sessions occasionally showed brief irradiance reductions due to cloud passages and declining solar altitude, which reduced light incidence on the compound parabolic collector (CPC). Although instantaneous irradiance fluctuated during these periods, the cumulative solar exposure during most runs remained sufficient to sustain measurable photocatalytic activity without auxiliary lighting. Fig. 2 presents the hourly variation of global horizontal irradiance between 08:00 and 17:00 BST, with shaded bands indicating short-term cloud variability recorded during the Analytical model campaign.

3.2. *Pollutant removal performance*

The degradation efficiencies of the selected emerging pollutants—atrazine, imidacloprid, and sulfamethoxazole—varied with the time of day and corresponding solar intensity. Under synthetic agricultural runoff conditions, noon Analytical models produced the highest removal efficiencies, achieving 92 ± 4% for atrazine, 86 ± 6% for imidacloprid, and 79 ± 5% for sulfamethoxazole after 60 min of illumination. These results demonstrate that the CPC reactor achieved substantial pollutant removal under natural sunlight.

During morning operations, lower irradiance levels corresponded to slower degradation rates. After one hour of treatment, removals decreased to 61 ± 7%, 53 ± 8%, and 45 ± 7% for atrazine, imidacloprid, and sulfamethoxazole, respectively. Afternoon trials exhibited intermediate efficiencies, typically ranging from 72% to 83% across the tested compounds. Fig. 3 compares pollutant removal efficiencies at morning, noon, and afternoon operating periods.

When Analytical models were conducted using real River Tame water, overall removal efficiencies decreased by approximately 20–35% relative to the synthetic matrix. The river water exhibited higher turbidity (6.1 ± 1.2 NTU) and dissolved organic carbon (7.4 ± 1.3 mg L^{-1}), which are known to influence light transmission and

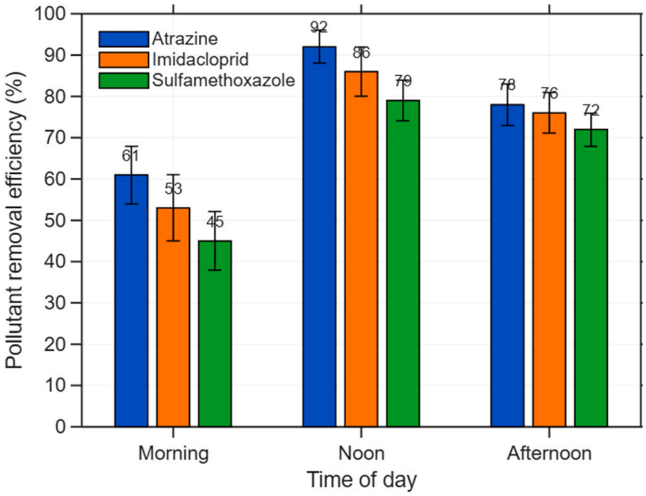

Fig. 3. Time-of-Day Efficiency (Clustered Bar Chart) generated according to *Catalysis Today* visual standards.

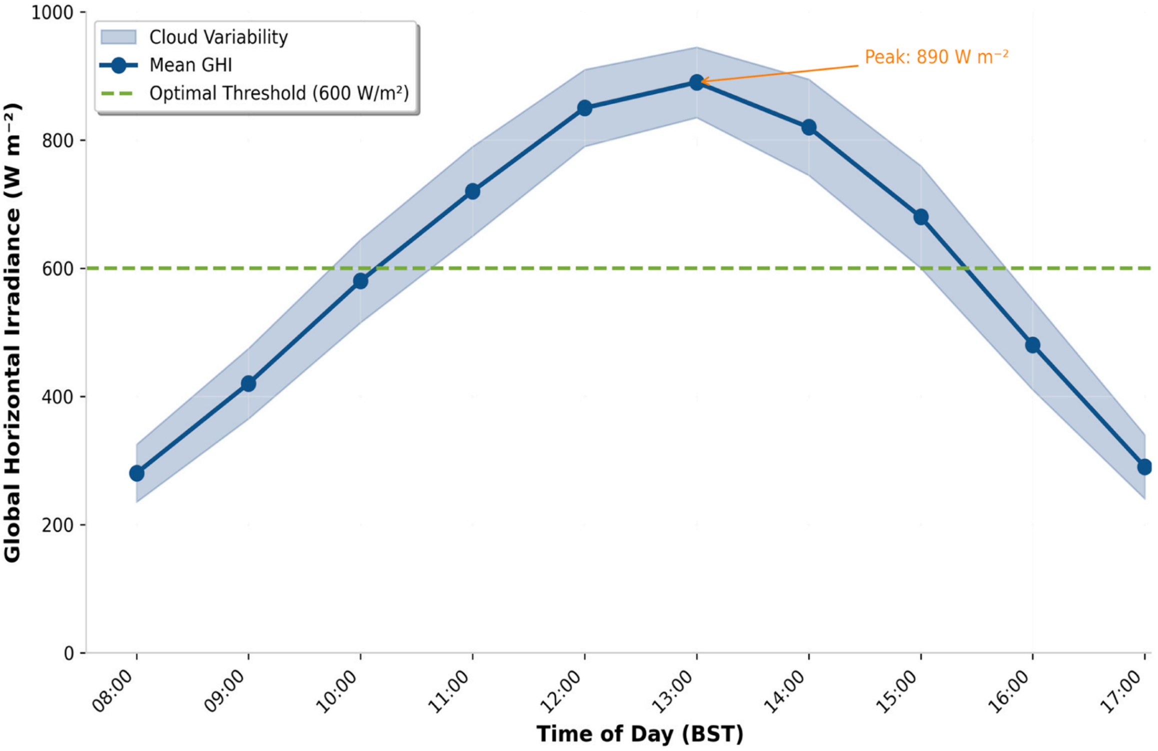

Fig. 2. Diurnal variation of global horizontal irradiance (GHI) during the experimental campaign, showing mean values and variability bands representing cloud interference and dashed line indicates the optimal operational threshold (600 W m^{-2}).

radical availability in photocatalytic systems. These factors likely contributed to reduced reaction rates, although the individual effects of turbidity and dissolved organic matter were not analytically separated in the present study. Despite this reduction, measurable degradation of pollutants was still observed under natural water conditions.

3.3. *Kinetic behaviour and irradiance relationship*

Pollutant degradation followed apparent first-order behaviour over the 60-minute reaction period. Apparent rate constants (k_{app}) increased with increasing irradiance, indicating a positive relationship between solar intensity and reaction rate. Linear regression analysis produced the following empirical relationships between global horizontal irradiance (GHI) and k_{app}:

$$\text{Atrazine}: \quad k_{app} = (2.2 \pm 0.2) \times 10^{-5} \cdot GHI + 0.004 \left(R^2 = 0.88, p < 0.01, n = 24\right)$$

$$\text{Imidacloprid}: \quad k_{app} = (1.9 \pm 0.3) \times 10^{-5} \cdot GHI + 0.003 \left(R^2 = 0.84, p < 0.01, n = 24\right)$$

$$\text{Sulfamethoxazole}: \quad k_{app} = (1.5 \pm 0.3) \times 10^{-5} \cdot GHI + 0.002 \left(R^2 = 0.86, p < 0.01, n = 24\right).$$

These results indicate statistically significant positive correlations between solar irradiance and photocatalytic degradation rates within the irradiance range examined.

Here, GHI is expressed in W m^{-2} and k$_{app}$ in min^{-1} . The positive correlations ($R^2 > 0.84$) indicate that higher solar intensity generally corresponded to faster degradation rates during the Analytical models. However, these relationships should be interpreted as empirical correlations within the tested irradiance range rather than as direct mechanistic proof of a photon-limited regime. From a photocatalytic reaction perspective, degradation of organic pollutants on TiO_2 surfaces is often described using the Langmuir–Hinshelwood kinetic model, where reaction rates depend on both surface adsorption and photon-induced radical formation. Under the dilute pollutant concentrations used in this study, the Langmuir–Hinshelwood expression can be simplified to a pseudo-first-order rate law. The linear relationship observed between $-\ln(C/C0)$ and irradiation time therefore indicates that the system behaved consistently with pseudo-first-order photocatalytic kinetics within the investigated concentration range. When river-water matrices were used, regression slopes remained statistically similar ($p > 0.05$), while intercept values decreased slightly. This shift suggests that background matrix components influenced baseline degradation rates while maintaining a similar irradiance dependence. Fig. 4 presents semi-log kinetic plots illustrating first-order degradation behaviour under different irradiance conditions.

3.4. *Influence of solar intermittency*

Transient cloud cover caused short-term fluctuations in irradiance during several analytical model runs. Reductions in GHI exceeding approximately 150 W m^{-2} for several minutes were associated with temporary decreases in pollutant degradation rates. Nevertheless, when the cumulative solar energy received during a 60-minute Analytical model was comparable, overall removal efficiencies generally differed by 8–12% relative to clear-sky runs.

These observations indicate that total photon exposure over the reaction period was a useful indicator of overall treatment performance under variable outdoor conditions.

3.5. *Irradiance-responsive operation*

To explore potential operational implications of the irradiance–kinetic relationship, treatment periods were analysed using a simple threshold approach in which reactor operation was considered effective when the 10-minute rolling mean GHI exceeded 600 W m^{-2}. Using the analytical model dataset, a post-analysis comparison suggested that concentrating operations within higher-irradiance intervals could increase the daily pollutant mass treated by approximately 32% (95% CI: 24–39%) relative to a fixed schedule.

It should be noted that this estimate is based on retrospective analysis of the Analytical model dataset rather than a fully automated control Analytical model. The results nevertheless illustrate the potential benefit of aligning reactor operation with periods of higher solar intensity.

3.6. *Catalyst stability and reuse*

Catalyst performance remained relatively stable over five consecutive reuse cycles conducted under midday conditions. The normalised apparent rate constant declined from 1.00 in the first cycle to approximately 0.82 after the fifth cycle, corresponding to an activity reduction of roughly 18%.

This decrease may be associated with gradual surface fouling by reaction intermediates or natural organic matter rather than structural degradation of the catalyst. A brief rinse with deionised water partially restored catalytic activity to approximately 5% of the fifth-cycle value.

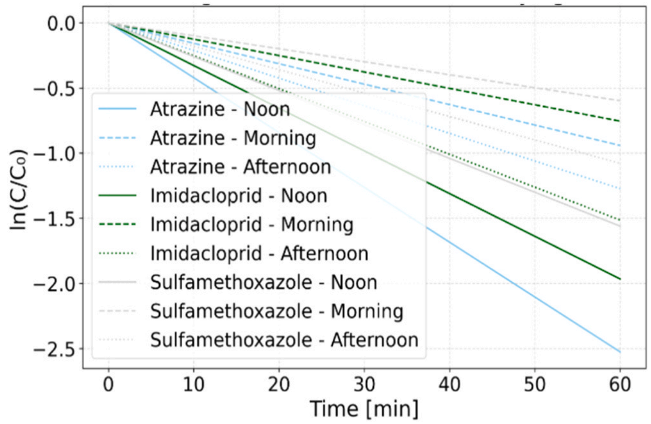

Fig. 4. First-order degradation kinetics of atrazine, imidacloprid, and sulfamethoxazole in the solar CPC reactor. Semi-log plots ($-\ln(C/C0)$ versus time) illustrate pseudo-first-order degradation behaviour under different solar irradiance conditions recorded during outdoor Analysis.

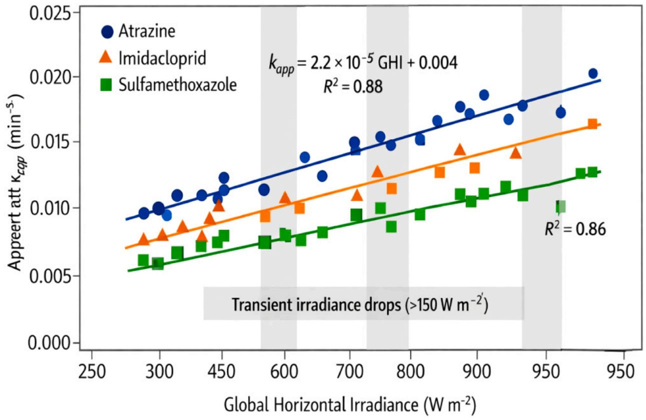

Fig. 5. Relationship between global horizontal irradiance (GHI) and apparent degradation rate constants (kapp) for the investigated pollutants during outdoor CPC reactor experiments. The regression lines illustrate the empirical dependence of photocatalytic degradation rates on solar irradiance.

No measurable titanium leaching was detected during the Analytical models. Fig. 5 illustrates the relationship between transient irradiance changes and degradation rate response.

3.7. *Reduction of ecotoxicity*

Bioluminescence inhibition assays with Aliivibrio fischeri were conducted to assess changes in potential toxicity following treatment. Luminescence inhibition decreased from 42 ± 6% in untreated samples to 12 ± 5% following photocatalytic treatment. This reduction indicates that the degradation of the target contaminants was accompanied by a measurable decrease in acute toxicity within the tested conditions.

3.8. *Summary of observed patterns*

Overall, reactor performance varied systematically with solar intensity and time of day, with midday conditions providing the highest and most stable degradation rates. The observed correlations between irradiance and apparent rate constants indicate that solar availability played an important role in determining treatment performance during the outdoor Analytical models. Although natural water matrices reduced removal efficiency relative to synthetic solutions, pollutant degradation and toxicity reduction were still achieved under field conditions. Catalyst reuse tests demonstrated moderate stability over multiple cycles. Fig. 6 summarises catalyst activity retention across the five reuse Analytical models.

4. Discussion

4.1. *Influence of natural solar conditions*

The results highlight the importance of evaluating photocatalytic systems under real sunlight conditions. The positive relationship between the apparent rate constant (k_{app}) and global horizontal irradiance (GHI) indicates that higher solar intensity generally leads to faster degradation of the target pollutants. Rather than demonstrating a new photocatalytic mechanism, these results provide field-based confirmation of irradiance-dependent behaviour under natural outdoor conditions [37–39].

Natural sunlight differs significantly from laboratory light sources because its intensity and spectral distribution vary continuously throughout the day. Artificial UV lamps are often used in photocatalysis research because they provide stable irradiation conditions. However, such laboratory conditions may not fully represent the variability encountered in outdoor applications. The present study, therefore, complements laboratory investigations by demonstrating how photocatalytic performance changes under real solar variability [40,41].

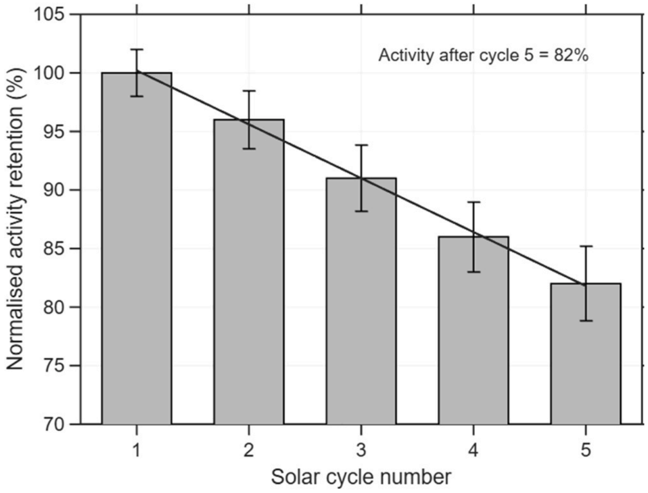

Fig. 6. Catalyst reusability during five consecutive photocatalytic cycles under solar irradiation. The normalised activity retention represents the relative degradation rate constant compared with the first cycle.

4.2. *Influence of time-of-day operation*

Differences in pollutant removal across the morning, noon, and afternoon were primarily attributable to changes in solar irradiance. Analytical models were primarily attributable to changes in solar irradiance. Midday runs produced higher apparent rate constants than those in the morning or late afternoon, reflecting the higher and more stable solar intensity observed during those hours.

These observations suggest that aligning treatment periods with higher sunlight availability may improve reactor productivity in outdoor systems. The dataset also indicates that degradation efficiency decreases when irradiance drops below approximately 600 W m^{-2}. However, this threshold should be interpreted as an approximate value specific to the conditions tested in this study. Further analytical model validation would be required before implementing automated irradiance-based control strategies [42–44].

4.3. *Influence of water matrix composition*

Analytical models performed using real River Tame water showed lower degradation efficiencies than those conducted in the synthetic runoff solution. This reduction was associated with higher turbidity and dissolved organic carbon concentrations in the natural water samples [45,46].

Turbidity can reduce light penetration into the reactor suspension, while natural organic matter can interact with reactive species generated during photocatalysis. Because the individual contributions of these factors were not isolated analytically, the results should be interpreted as a combined matrix effect rather than as evidence of a single dominant mechanism.

Despite this reduction in performance, pollutant removal was still observed in the natural water matrix. This suggests that solar photocatalysis may remain applicable in moderately turbid waters, although pretreatment steps such as settling or filtration could potentially improve performance in practice [47,48].

4.4. *Reactor operation and practical considerations*

The compound parabolic collector (CPC) reactor used in this study operated stably under varying solar conditions. The CPC's optical configuration allowed both direct and diffuse sunlight to reach the reaction tubes, which is advantageous in climates with frequent cloud cover.

The results indicate that outdoor photocatalytic performance depends not only on catalyst properties but also on reactor configuration and solar exposure conditions. In the present Analytical models, the recirculating slurry system-maintained catalyst suspension while allowing efficient exposure of the reaction mixture to sunlight.

Operational improvements, such as optimising exposure periods or integrating simple solar monitoring devices, could enhance system efficiency, although these were not implemented analytically in this work.

4.5. *Limitations of the study*

Several limitations should be acknowledged. First, the Analytical models were conducted during a summer period at a single geographical location. Solar intensity and spectral composition vary seasonally and geographically, and these variations may influence photocatalytic performance.

Second, the photocatalyst used in this study was commercial TiO_2 P25, which is primarily activated by ultraviolet light. Consequently, the system performance reported here reflects the UV fraction of natural sunlight rather than the full solar spectrum.

Third, only three representative micropollutants were examined. Agricultural runoff can contain complex mixtures of pesticides, pharmaceuticals, and other organic compounds. Future studies should therefore examine broader contaminant mixtures and transformation products formed during photocatalysis.

4.6. Environmental implications

Solar photocatalysis offers a potential approach to reducing trace organic contaminants in agricultural runoff, using sunlight as the primary energy source. The outdoor Analytical models conducted here demonstrate that measurable pollutant removal and toxicity reduction can be achieved under natural sunlight conditions.

Although further work is needed to evaluate long-term stability, seasonal performance, and large-scale operation, the results suggest that solar-driven photocatalytic systems may contribute to decentralised water treatment strategies in areas with limited access to conventional treatment infrastructure.

5. Conclusion

This study evaluated the performance of a solar-driven TiO_2 photocatalytic system operated in a compound parabolic collector (CPC) reactor under natural outdoor conditions to treat contaminants in agricultural runoff. Analytical models conducted under real sunlight demonstrated that degradation efficiencies varied systematically with solar irradiance. Within the irradiance range observed during the campaign (260–910 $W\ m^{-2}$), apparent reaction rate constants increased with increasing solar intensity ($R^2 = 0.84–0.88$), indicating a consistent empirical relationship between sunlight availability and pollutant degradation rates.

Under synthetic agricultural runoff conditions, the system achieved removal efficiencies of 92 ± 4% for atrazine, 86 ± 6% for imidacloprid, and 79 ± 5% for sulfamethoxazole during noon-hour operation. Lower efficiencies were observed in natural river water, where higher turbidity and dissolved organic carbon reduced photocatalytic activity by approximately 20–35%. Despite this matrix effect, measurable reductions in pollutant levels and toxicity were still achieved under outdoor conditions.

Catalyst reuse: Analytical models showed moderate stability, with approximately 82% of the initial activity retained after five consecutive cycles. The observed activity loss was modest and partially recoverable after simple rinsing, suggesting that catalyst fouling rather than structural degradation may contribute to performance decline during repeated operation.

Analysis of the analytical model dataset further indicated that aligning treatment periods with higher solar irradiance could improve reactor productivity. A retrospective comparison suggested that concentrating operations during higher-irradiance intervals could increase the total daily pollutant mass treated by approximately 32%. However, this estimate is based on post-analysis of analytical model data rather than direct automated control of analytical models.

Overall, the findings demonstrate that solar photocatalysis with TiO_2 can effectively degrade selected agricultural contaminants under natural sunlight. By linking degradation performance with real-time irradiance measurements, the study provides practical insights into how solar availability influences outdoor photocatalytic treatment systems. These results contribute to the understanding of solar-driven water treatment processes and highlight the potential of CPC-based photocatalytic reactors for decentralised environmental remediation.

CRediT authorship contribution statement

Sandra C. Akaelu: Supervision, Software, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Conceptualization. **Lukman O. Kolawole:** Writing – review & editing, Writing – original draft, Validation, Supervision, Investigation, Funding acquisition, Data curation, Conceptualization. **Chijioke C. Chuwa:** Visualization, Resources, Project administration, Investigation, Funding acquisition, Formal analysis, Data curation. **Stephanie O. Akaelu:** Writing – review & editing, Visualization, Validation, Supervision, Software, Methodology, Investigation, Formal analysis, Data curation. **Ifeoluwa E Elemure:** Writing – review & editing, Visualization, Project administration, Methodology, Investigation, Funding acquisition, Data curation, Conceptualization. **Abiodun F Ibidunmoye:** Writing – review & editing, Visualization, Validation, Supervision, Project administration, Investigation, Funding acquisition, Formal analysis, Data curation. **Adeyinka G. Ologun:** Visualization, Validation, Supervision, Software, Project administration, Investigation, Funding acquisition, Formal analysis, Data curation. **Francis T. Omigbodun:** Writing – review & editing, Visualization, Supervision, Software, Methodology, Investigation, Formal analysis, Data curation.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

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