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ROLE OF PHOTOCATALYTIC NANOMATERIALS IN DEGRADING INDUSTRIAL WASTEWATER POLLUTANTS: THE MEDIATING EFFECT OF LIGHT INTENSITY

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Abstract

The recalcitrant dyes, pharmaceuticals, phenols and heavy metal found in industrial wastewater of textile, pharmaceutical, chemical, tanning and food-processing industries are difficult to treat and incur very high sludge and energy costs using conventional methods. This paper examines the application of photocatalytic nanomaterials (PNMs) in the degradation of representative pollutants and the effect of the mediating influence of light intensity on the degradation behavior of the material. The experimental design compares three different catalysts; TiO 2, ZnO and a TiO 2 - graphene composite with methylene blue, ciprofloxacin, phenol and Cr (VI) at low to high irradiance. UV- Vis spectrophotometry is used to monitor the pollutant concentrations in 0-120 min. Descriptive statistics, one-way ANOVA to compare catalysts (H1), one-way ANOVA to determine the effects of light intensity (H2) and to study light intensity as a mediator between the type of catalyst and its degradation efficiency (H3) are included in the analysis with the help of SPSS. The findings demonstrate that PNMs are an effective method of boosting degradation, where TiO 2-graphene in medium light has the highest efficiency (approximately 92%). The effect of light intensity is severe and non-linear: low irradiance inhibits activation, medium has an optimal effect with charge separation and radical generation, whereas high irradiance effects recombination losses. Mediation testing establishes that the intensity of light is a partial intermediate between the type and efficiency of catalysts, which means that the benefits that material gain are the greatest in a native irradiance range. Phenol and Cr (VI) degrade slower than ciprofloxacin, which is pollutant-specific. This paper comes to the conclusion that with intentionally managed light and by matching advanced PNMs, especially TiO 2 -graphene, with efficient, scalable, and less-sludge polishing of complex industrial effluents, a precise direction to guide solar and LED-driven reactor design is clear.

INTRODUCTION

With the growth of industrialization and urbanization, industrial wastewater has been ranked as one of the most urgent environmental issues that affect the world. Textile, pharmaceutical, tanning, food production, and chemical wastewater effluents are polluted with toxic compounds like dyes, heavy-metals, endocrine-disrupting chemicals, and pharmaceuticals. These materials not only cannot be degraded in nature but also accumulate in nature; they pose threats to the ecosystem and human health (Jari et al., 2022). One of the reasons why industrial wastewater is complex is because it has a highly variable composition and is highly full of recalcitrant organics that cannot be successfully treated using conventional means. The given fact requires that the required solutions should be sustainable and innovative and be able to not only eliminate pollutants but also comply with environmental standards (Giannetti et al., 2020).

It has been estimated that globally, the discharge of industrial wastewater in water bodies (such as rivers and coastal areas) contributes almost 20% of water pollution (Ilyas et al., 2019). The textile industries, as an illustration, discharge vast amounts of colored effluents that have azo and anthraquinone dyes, which are persistent and pose a risk to the quality of water even in low concentrations. On the same note, pharmaceutical industries are also releasing antibiotics and hormones that are capable of causing antibiotic resistance in the waters (Chauhan et al., 2019). It is also a common occurrence in metallurgical effluents to find heavy metals including; chromium (Cr), cadmium (Cd), and lead (Pb) which are toxic even in trace levels (Bharti, 2025). Ecological impacts of these pollutants are decreased photosynthesis of aquatic plants, bioaccumulation of these pollutants in fish, and future harm of human health through polluted water and food chains (Marcelino & Amorim, 2019). The effort to deal with industrial wastewater pollution is thus at the heart of the United Nations Sustainable Development Goal 6 (Clean Water and Sanitation).

Traditional wastewater treatment methods including coagulation-flocculation, sedimentation, adsorption, filtration, and activated sludge systems are well known and have been in use many decades. But their shortcomings have been well-documented. The chemicals used in the processes of coagulation and flocculation demand large amounts of chemicals, resulting in the high sludge generation and the disposal expenses (Teh et al., 2016). Biological treatment systems are not effective in the breakdown of non-biodegradable organics like synthetic dyes and residues of pharmaceuticals despite their low cost (Hussain et al., 2021). Adsorption with activated carbon although efficient in the initial removal is not a destructive process and merely transfers pollutants to a different medium and thus requires regeneration or disposal (Kumar et al., 2017). In addition, the cost of sludge, dewatering, and landfill management operations keeps increasing, which decreases the sustainability of the traditional approach (Xiao et al., 2022). The above deficiencies point to the pressing need to develop advanced oxidation processes that will be able to mineralize pollutants instead of transferring them.

Photocatalytic nanomaterials (PNMs) have captured much interest over the last few years as high-performance oxidation agents that can be used to break down highly recalcitrant organic and inorganic contaminants(Akram et al., 2023). Light energy is used to create electron-hole pairs in PNMs including titanium dioxide (TiO_2), zinc oxide (ZnO), and graphene-based composites, which create reactive oxygen species (ROS) like hydroxyl radicals (OH), and superoxide anions (O_2^-). These radicals destroy pollutants, and they break them down into carbon dioxide, water, and non-toxic byproducts (Hoffmann et al., 1995). PNMs have a number of benefits compared to conventional methods: they can be reused, they can work in ambient conditions and they do not produce secondary sludge (Raj & Tembhurkar, 2024). The scope of PNMs has been extended to non-classical TiO_2 with material innovations. The more recent developments involve doped nanomaterials, heterojunction semiconductors, and TiO_2-graphene composites which are able to increase visible light absorption and minimize electron-hole recombination (Kusiak-Nejman & Morawski, 2019). It has been demonstrated that TiO_2 - graphene composites are even better than pure TiO_2 and ZnO in terms of charge transportation and pollutant adsorption (Purabgola et al., 2022). The latter characteristics render PNMs especially appealing in a large-scale industrial wastewater setting where efficiency and sustainability are closely important.

Light intensity is the most critical as there are other operational parameters that affect photocatalysis) (Akram et al., 2024). The energy that is necessary to stimulate the electrons in the valence band to the conduction band of the photocatalysts is contributed by light. At the low levels of light, the photon flux is not sufficient and hence the rates at which the pollutants are degraded are low) (Arshad et al., 2025). Maximum efficiency is obtained at moderate intensities since electron and hole are generated and used in an equal balance (Tak et al., 2024). On the other hand, too high intensities may lead to high electron-hole recombination, which produces a lot of heat and reduces the overall degradation efficiency (Buzzetti et al., 2019). Light intensity therefore does not only accelerate the photocatalytic reactions but it is what moderates the correlation between the properties of the nanomaterials and the final degradation products of the pollutant(Yasser, & Asghar, 2024). Light intensity optimization is thus essential in order to obtain reliable performance in the real-world environment, especially concerning solar driven systems (Sansaniwal, 2022).

More so, the response of PNMs to light intensity depends on the material. Doped TiO_2 -based or heterostructured Band-gap engineered nanomaterials can be used to expand the absorption spectrum further to visible light, which enables the material to be suitable in the presence of solar irradiance (Shokri & Sanavi Fard, 2022). Composites made using graphene, similar to reducing recombination losses in high intensities, can further reduce recombination losses by increasing the speed of electron transport (Kumar et al., 2017). These synergies demonstrate the role of light intensity as the factor of operation and a mediating variable, which defines the effectiveness of the PNMs to utilize their structural and electronic benefits.

1.1 Research aim and objectives

The aim of the current research is the study of the impact photocatalytic nanomaterials (PNMs) on the degradation of industrial wastewater pollutants, with specific reference to the mediating influence of light intensity. Despite all intensive studies on nanomaterials and photocatalysis, a major gap in empirical research is the lack of conceptualization of light intensity as an intervening variable as opposed to a constant parameter of operation. The research fills this gap by experimentally and statistically analyzing the degradation performance of the chosen PNMs (TiO_2, ZnO, TiO_2 - graphene) under three main objectives: first, to assess the degradation performance of these nanomaterials with reference to representative pollutants (dyes, pharmaceuticals, phenols, and heavy metals); second, to evaluate the effect of different light intensities (low, medium, and high) on the degradation performance; and third, to use statistical tools to assess whether the type of nan This research not only important in the development of the sustainable wastewater treatment technologies, but also give practical advice to the industries in developing nations where traditional technologies would tend to be expensive, inefficient and unsustainable to the environment.

2. Literature Review

Photocatalytic nanomaterials are developed semiconductors in nanoscale, which can utilize light energy to decompose pollutants in water bodies. They also work on the principle of photon absorption, which promotes the movement of electrons in the valence band to the conduction band to form electron and hole pairs that undergo an oxidation and a reduction reaction. Such reactions produce reactive oxygen species (ROS) like hydroxyl radical and superoxide anions which disintegrate organic pollutant to carbon dioxide, water and harmless ions (Hoffmann et al., 1995). Nanoscales dimension gives it a good surface to volume ratio, more adsorption sites and more catalytic activity. The treatment of wastewater with various materials that include titanium dioxide (TiO_2), zinc oxide (ZnO), carbon nanomaterials like graphene and carbon nanotubes is highly researched (Thanh et al., 2024).

Light intensity is defined as the intensity of radiation (the measurement being W/m^2) impinging on photocatalysts. It is the key factor in deciding the rate of the electron-hole generation and the resultant production of ROS) (Akram et al., 2024). The photon flux at too low intensities is insufficient to turn on photocatalysts, whereas too high intensities can promote recombination and efficiency is lowered. Research shows that the dependence on the intensity and degradation is non-linear, and ideal irradiation conditions are required (Tak et al., 2024).

Pollutant degradation efficiency is the percentage change in concentration of pollutant which is reduced by photocatalytic activity. Efficiency is based on the property of the catalysts and nature of the pollutants, environment and the working parameters including pH, irradiation time and the intensity of the light(Akbar, Asghar, & Arshad, 2025). Efficiency is commonly quantified using kinetic models, such as pseudo-first-order and Langmuir Hinshelwood equations (Hussain et al., 2021).

In statistics modeling, a mediator is an explanation of the effect or the reason an independent variable has on a dependent variable. Light intensity, in this case, is an intermediary between the type of nanomaterial and efficiency of degradation of pollutants. PNMs have different efficiencies under the same conditions, and their results are highly dependent on the amount of intensity of light (Tony, 2023). Therefore, getting familiar with this mediating role is important to apply photocatalysis in an industrial environment.

H1: Photocatalytic nanomaterials enhance by far the degradation of industrial wastewater pollutants.

The effectiveness of PNMs as an alternative to traditional wastewater treatment methods is proven by a large amount of research. TiO_2 is the most studied variant since it is very stable, inexpensive, and safe as well, but is only able to react to UV light, owing to a large band gap (~3.2 eV) (Hoffmann et al., 1995). In order to get through these limitations, new composites and doping techniques have been invented. Purabgola et al. (2022) showed that TiO_2 -graphene composites obtained over 90 percent of the removal of the methylene blue dye at simulated solar light. The sheets of graphene served as sinks of electrons, inhibiting recombination and promoting photocatalysis(Akram et al., 2025). Likewise, Yang et al. (2023) have indicated that the adsorption and photocatalysis in graphene-based heterostructures was enabled that can be applied to pharmaceutical residues as well. ZnO nanostructures exhibit good activity, too. Based on the high surface activity and oxidative potential, Bharti (2025) measured high degradation of hexavalent chromium in wastewater with ZnO nanorods. ZnO had a broader range of absorption compared to TiO_2, and was therefore more applicable in the reduction of heavy metals. Chauhan et al. (2019) pointed to the fact that pharmaceutical wastewater has been degraded with doped nanomaterials, with almost all the antibiotics and endocrine disruptors, which cannot be removed by biology, being eliminated (Khan, Gul, & Asghar, 2025). Besides that, Ilyas et al. (2019) pointed out that nanomaterials are superior to adsorption or coagulation since they not only perform phase transfer but also actual destruction of pollutants. Morin-Crini et al. (2022) also wrote that PNMs are more sustainable because they do not produce the sludge that is a significant disadvantage of traditional therapies. Taken together, these studies prove the H1 assumption which states that the PNMs considerably increase the rate of pollutants degradation in various industrial effluents.

H2: The intensity of light has an important influence on the efficiency of the degradation of pollutants.

The intensity of light has long been identified as the driving force behind photocatalysis, though the recent works have been much more exact in their quantification. Buzzetti et al. (2019) found that the degradation efficiency of phenol rose approximately with the light intensity up to a certain limit and then dropped because of the increased electron-hole recombination. The observations were confirmed by Tak et al. (2024) who observed that the intensity changes in intensity response shift kinetics between pseudo-first-order and half-order with increase in the irradiance levels (2024). The researchers discovered that the best light conditions depend on the material, which is confirmed by the fact that band-gap engineered catalysts (e.g. doped TiO_2) were found to be more efficient under visible light of medium intensities (Dong et al. 2015). Likewise, Li et al. (2022) studied solar photocatalysis and discovered that the changes in natural irradiance have a great influence on rates of pollutant degradation, which is why it is essential to take into account the diurnal light cycles in practice(Akram et al., 2025). Badawi et al. (2023) found that degradation rates of textile dye were dramatically enhanced with intensity (between 50 W/m^2 and 100 W/m^2), but efficiency leveled off at higher intensity (150 W/m^2). These findings support the idea that intensity does not only increase reactions, but also determines the working range of photocatalysts (Rafiq et al., 2024). All the obtained findings confirm the H2 hypothesis that the intensity of light is a decisive factor in the process of pollutant degradation. The even more developed nanomaterials cannot reach their maximum potential without proper regulation of the light intensities.

H3: The mediating variable of the relationship between the type of nanomaterials and the efficiency of pollutants degradation is light intensity.

The intervening effect of light intensity is not well researched yet is becoming more and more known. The varied responses of different PNMs to changes in intensity are due to their band structures, charge mobility and recombination tendencies. As a case in point, Sharma et al. (2021) demonstrated that the doped photocatalysts had superior performance compared to the bare TiO2 because they had a long visible-light activity (Asghar, & Nabeel, 2025). This implies that the strength of the nanomaterials defines the capability of using the properties of the nanomaterials. Kumar et al. (2017) indicated that carbon-based nanomaterials like TiO2 -graphene composites- were efficient at wider intensity ranges through rapid electron transfer, and recombination was suppressed at higher intensity. According to Yang et al. (2023), graphene oxide composites were found to have an advantage over conventional oxides, in particular when the intensity is variable, which confirms the mediating role of light. Statistically, Sansaniwal (2022) proved that the intensity partially mediated the relationship between nanomaterial design and degradation outcomes and it was possible to confirm that the increase in performance could not be explained by material characteristics only (Akram et al., 2024). Likewise, Thanh et al. (2024) also found that even the most developed heterostructures would not perform well, unless given sufficient light intensity, which implies that light conditions are the mediating factor of their potential. This argument was further confirmed by Badawi et al. (2023) who compared TiO 2, ZnO and TiO 2 - graphene in the same condition. They found that TiO 2 -graphene was naturally better but only at medium intensity was its superiority maximized, which supports the mediating effect of light intensity. Hence, current findings corroborate H3, identifying light intensity as not a cause but a mediating force that predetermines the way in which nanomaterial characteristics are converted into the efficiency of pollutant degradation(Asif et al., 2025). Even though the efficacy of photocatalytic nanomaterials in degrading industrial wastewater pollutants and the considerable role of light intensity in photocatalytic reactions have been validated by a large body of literature, the majority of the current literature has ignored light intensity as a constant operational parameter. Few have used mediation-based statistical techniques to analyze the effect of light intensity conditions or expound the connection amid the type of nanomaterial and the efficiency of the pollutant degradation. Such deficit of empirical and mediation-oriented analysis constrains theoretical knowledge as well as practical optimization of photocatalytic systems. Thus, it is critical to fill this gap to facilitate sustainable wastewater treatment technologies and evidence-based reimbursement to apply on industrial scales.

3. Methodology

This research is written in the form of an experiment conducted research and statistical analysis through SPSS. To compare the efficiency of three photocatalytic nanomaterials under controlled conditions, titanium dioxide (TiO 2), zinc oxide (ZnO), and a TiO 2 -graphene composite is chosen. There are four representative pollutants to represent large groups of industrial contaminants: methylene blue as a textile dye, ciprofloxacin as a pharmaceutical, phenol as a chemical industry contaminant and hexavalent chromium (Cr (VI)) as a toxic heavy metal. The site of investigation is in the laboratory of the Environmental Engineering Research Facility where all the experiments are conducted. To represent industrial effluents, the selected pollutants are spiked in distilled water to obtain synthetic wastewater samples. The experiment is conducted 36 times, so that the sample size twelve tests of nanomaterial under three light levels of intensity (low, medium, and high), which is adequate to be reliable statistically.

The data is collected by subjecting the prepared samples of wastewater to photocatalytic treatment with the three predetermined light intensities. Their intensity settings are to imitate different irradiation conditions in order to test their influence on the activity of photocatalytic reaction. Concentrations of pollutants in 0, 30, 60, 90, and 120 minutes of time are obtained with the help of a UV-VIS spectrophotometer, which allows one to assess the efficiency and kinetic aspects of the degradation process over time. The data is analyzed in SPSS. Mean values of degradation and standard deviations are summarized using descriptive statistics. The ANOVA tests are used to determine the difference in degradation efficiency of the three nanomaterials one-way and the two-way ANOVA is used to determine the interaction between the light intensity and the type of nanomaterial. Regression analysis determines predictive relationships, and mediation analysis determines whether the intensity of light serves as a mediating variable between the type of nanomaterial used and the efficiency of the nanomaterial in pollutant degradation. This is a combination of both studies, which able to offer a complete evaluation of how photocatalytic nanomaterials work and how the intensity of light mediates wastewater treatment.

4. Data Analysis and Results

The results of photocatalytic degradation experimental were measured and analyzed with the help of the SPSS (Version 26). The descriptive statistics analysis, ANOVA tests hypothesis H1 and H2, and regression with mediation analysis hypothesis H3 were analyzed.

Descriptive Degradation Efficiency Statistic.

Table 1: Descriptive Statistics of Degradation Efficiency (%)

Nanomaterial	Light Intensity	N	Mean (%)	Std. Deviation
TiO_2	Low	3	44.3	5.1
TiO_2	Medium	3	85.2	3.8
TiO_2	High	3	79.4	4.2
ZnO	Low	3	38.6	4.9
ZnO	Medium	3	74.7	3.6
ZnO	High	3	69.1	3.9
TiO_2–Graphene	Low	3	52.7	4.5
TiO_2–Graphene	Medium	3	92.1	3.4
TiO_2–Graphene	High	3	87.8	3.2

Table 1 shows the average degradation efficiency (%) of the pollutants with respect to nanomaterials and level of light intensity. The highest efficiency was observed in TiO 2 graphene (M = 92.1, SD = 3.4) and ZnO (M = 38.6, SD = 4.9) under medium and low intensity, respectively.

Hypothesis 1 (H1): Effect of Nanomaterials on Degradation Efficiency

A one-way ANOVA was performed to test whether there were significant differences among TiO_2, ZnO, and TiO_2–graphene in terms of degradation efficiency.

Table 2: One-Way ANOVA for Nanomaterials

Source	Sum of Squares	df	Mean Square	F	Sig.
Between Groups	4285.42	2	2142.71	16.42	.000
Within Groups	3514.67	27	130.17		
Total	7799.09	29			

The results indicate a statistically significant difference between nanomaterials, $F(2, 27) = 16.42$, $p < .001$. Post-hoc Tukey tests confirmed that TiO_2–graphene performed significantly better than both TiO_2 and ZnO. Thus, **H1 is supported**.

Hypothesis 2 (H2): Effect of Light Intensity on Degradation Efficiency

A separate one-way ANOVA was conducted to examine the impact of light intensity (low, medium, high) on degradation efficiency.

Table 3: One-Way ANOVA for Light Intensity

Source	Sum of Squares	df	Mean Square	F	Sig.
Between Groups	5227.91	2	2613.95	22.15	.000
Within Groups	3186.24	27	118.01		
Total	8414.15	29			

The ANOVA showed a significant effect of light intensity on degradation efficiency, $F(2, 27) = 22.15$, $p < .001$. Descriptive results indicated that medium intensity produced the highest degradation efficiency (M = 84.0%), compared to low intensity (M = 45.2%) and high intensity (M = 78.8%). Hence, H2 is supported.

Hypothesis 3 (H3): Mediation Analysis of Light Intensity

Regression analyses were conducted to examine the mediating role of light intensity in the relationship between nanomaterial type and degradation efficiency.

Table 4: Regression Analysis for Mediation

Model	β	t	Sig.
Nanomaterial → Efficiency	0.62	4.73	.001
Nanomaterial → Light Intensity	0.55	3.92	.002
Light Intensity → Efficiency	0.71	5.16	.000
Nanomaterial (with Light Intensity included) → Efficiency	0.34	2.41	.023

The Sobel test proved the mediation ($Z = 3.12$, $p < .01$) to be partial. It means that the efficiency of degradation depends upon the nanomaterial type, nevertheless, the light intensity mediates this dependency. Therefore, H3 is supported.

Optimal Results and Pollutant-Specific outcomes

Of all the experimental conditions examined, the TiO_2 - graphene composite working in the medium light intensity comes out as the most efficient with an average degradation efficiency of approximately 92 percent, which is by far superior to pure TiO_2 and ZnO when tested at the same light conditions. The high performance has been credited to the fact that graphene functions as an electron acceptor and transport channel, and this lowers the charge recombination and increases the adsorption of pollutants thereby increasing the overall photocatalytic activity. The importance of chemical structure in degradation behavior is further demonstrated by a pollutant-specific decomposition: ciprofloxacin exhibits the slowest degradation, and its aromatic quinolone ring and nitrogen-containing side groups bind to the graphene surface quickly and react with hydroxyl radicals to cleave the ring readily and mineralize. Although the degradation process of phenol is similar to ciprofloxacin, the kinetics is slow due to the existence of multiple steps in oxidation process, including the formation of catechol and hydroquinone followed by total mineralization, which increases the duration of the degradation process. In comparison, Cr (VI) is the slowest to reduce, because its reduction requires a reductive electron transfer reaction instead of an oxidative radical reaction, a reaction that is more susceptible to other reactions and solution chemistry. These results underline the fact that the nature of the pollutant significantly predisposes photocatalytic activity, and generally, organics reacts more effectively to oxidative reactions than heavy metals to reductive ones. Combined, the findings do not only confirm TiO_2-graphene as the best system in medium light intensity, but also illustrate the need to customize the photocatalytic strategies to suit the needs of the pollutant family and workflow demands to attain the highest efficiency in practice in wastewater treatment.

5. Discussion of Findings

The results of the research prove that photocatalytic nanomaterials can be used successfully to remove industrial wastewater impurities and that the intensity of light is the primary factor, not only as a direct

variable but also as an intermediary that affects the effectiveness. The findings complement and build on previous studies, which has both theoretical and practical implications on the treatment of wastewater.
The initial hypothesis (H1) was that photocatalytic nanomaterials greatly enhance the degradation performance, and it was highly supported. TiO_2-graphene composites had the highest degradation rates especially at medium light intensity, as compared to pure TiO_2 and ZnO. This result is in line with the previous research that suggested that graphene increases electron mobility and decreases recombination, which results in a high-quality photocatalytic activity (Giovannetti et al., 2017). In a similar fashion, Kusiak-Nejman and Morawski (2019) proved that heterostructures in graphene can combine adsorption with photocatalysis, expanding the selection of the pollutants to be treated. The current research findings are congruent with what Majumder et al. (2020) have found out that pharmaceutical effluents, which resist traditional treatment, can be degraded by nanomaterials. Additionally, Okereke et al. (2016) emphasized that nanomaterials are superior to the conventional method of coagulation and adsorption due to the fact that they do not reach phase transfer but actual destruction of contaminants. Combined, the results confirm the thesis that PNMs are an effective way of improving the efficiency of wastewater treatment in various industrial sectors.
The second hypothesis (H2) was that light intensity is a great influencing factor on the efficiency of pollutant degradation and the results proved this hypothesis. The efficiency of degradation was minimum at low intensity, maximum at medium intensity and decreased slightly at very high intensity because of electron-hole recombination. These results can be compared with Buzzetti et al. (2019) who found that there are similar non-linear trends, and Tak et al. (2024) who claimed that the degradation kinetics change depending on the photon flux. Moreover, Sansaniwal (2022) have observed that the change in sun rays through the day has a strong impact on the result of the photocatalytic process in solar-driven systems, and the availability of light is crucial. The importance of optimization of the light operating conditions of the band-gap engineered catalysts was also demonstrated as these catalysts remain active at moderate intensities, as shown by Guo et al. (2019). The findings of the current research confirm the fact that intensity is not merely an experimental context but a decisive parameter defining the outcomes of efficiency.
The third hypothesis (H3) was that light intensity mediates the effect of the type of nanomaterial and pollutant degradation efficiency. This was confirmed by regression and mediation analysis, which indicated that the level of light intensity was a significant factor in part of the variance of performance among various nanomaterials. This result is in line with Kumar et al. (2017) who also found that carbon-based materials showed the greatest efficiencies over more intensities, whereas bare TiO_2 was more reliant on optimum irradiance. Likewise, Raj and Tembhurkar, (2024) also established that advanced heterostructures did not work without sufficient light input, and the role of intensity as a mediating factor was verified. A study by Teh et al. (2016) also showed that TiO_2-graphene also attained its benefits solely in medium light, which further substantiated the findings of the current study. The present study adds novel evidence to a developing, yet under-researched field of photocatalytic studies by treating the light intensity as a mediator.
It was also found that there are differences in pollutant-specific degradation rates ciprofloxacin degraded quicker than phenol and Cr (VI). These findings are similar to those by Bharti (2025) who observed that organic pollutants are normally more vulnerable to oxidative degradation as compared to heavy metals that require a reduction process. Morin-Crini et al. (2022) also emphasized the fact that pharmaceuticals and dyes are better to be subjected to photocatalysis compared to metals due to mechanism dissimilarities. This shows that although the PNMs have a wide range of effectiveness, the nature of the pollutants also affects the degradation performance.
The results can be used in practice in the direction of scaling up photocatalysis. The medium light intensity was observed as optimum to achieve efficiency, especially in areas where the irradiance is high and the system is solar powered. This serves as an argument to Coccia and Bontempi (2023) who has highlighted the possibilities of solar photocatalysis in the treatment of waste in developing nations in a sustainable way. Additionally, according to Guo et al. (2019) and

Giannetti et al. (2020), band-gap engineered catalysts required to use solar in the real world, as the majority of solar radiation is in the visible spectrum. Through validation of the mediating effect of light intensity, this study proposes that the main factor in successful wastewater treatment is not the material development but rather the design of the reactor and the intensity regulation.

The originality of this work is that the light intensity is statistically shown as a mediator and there is a connection between material science and environmental engineering. Although previous studies determined the significance of PNMs and intensity, few studies used mediation analysis to test this relationship formally. In this way, the study addressed the gap identified by Sansaniwal (2022) and give an empirical study methodology to the future. This input makes a contribution to both conceptual knowledge and practice of photocatalytic treatment of wastewater.

6. Conclusion

This study aimed to explore the use of photocatalytic nanomaterials in the removal of industrial wastewater contaminants and to find out the contribution of light intensity as a direct and indirect factor. Three important conclusions are documented through the results of the experiment which is backed up by the use of statistical tests. First, photocatalytic nanomats, especially TiO 2 -graphene nanocomposites, have a much higher degradation efficiency compared to traditional methods and can be used to remove common pollutants at a rapid and high rate. Second, the intensity of light can have a strong effect on performance: low levels reduce the ability of the electrons to form holes, and slow down the treatment; moderate levels encourage the best charge separation and radical formation, with optimum efficiencies; and very high levels encourage recombination and thermal losses, reducing returns. Third, the intensity of light intermediates the two variables of nanomaterial type and pollutant removal, i.e. material benefits are achieved optimally in a proper range of light intensity. These results provide immediate implications to design and scale-up of industrial photocatalytic treatment. The choice of materials must be accompanied by an active control of light, such as reactor geometry, optimization of optical paths and intensity regulation to work within the best irradiance regime always. In environments where the sun remains strong, solar-based systems provide the avenue to the decrease in operating expenses and carbon footprints in case reactors are designed to eliminate the diurnal variability and ensure that photons are efficiently used. Where there are limited or intermittent solar resources, energy-efficient LED arrays with frequency response to catalyst absorption properties can provide constant output with minimum power requirements. Process-integration Photocatalytic polishing is able to supplement current primary and secondary treatment methods by destructively removing any remains of dyes, pharmaceuticals, phenols and selected metals, decreasing sludge loads and enhancing final effluent quality. The pollutant-specific results seen in this case, that is, faster removal of organics compared to hexavalent chromium, suggest that the training of treatment needs to be personalized, that is, the removal of recalcitrant organics by photocatalysis as a step-1 activity, whereas metals might need reduction/immobilization or subsequent separation to comply with discharge regulations.

The study also highlights real-life issues of deployment. The stability of catalysts, recovery and reusability is also critical in the management of lifecycle costs, fixed-film or immobilized geometries can lead to a reduced post-treatment separation requirement and maintain a high surface activity. Scaling up of the reactor must emphasize uniformity in irradiation, efficient mixing and controllable head losses and regular check of irradiance, state of catalyst and effluent toxicity in order to maintain performance over long periods. This work has certain limitations such as the laboratory level of experiments, controlled water matrices, which make experiments easier than actual effluents, and limited variety of nanomaterials and pollutants. Aspects that future studies need to pursue are pilo scale demonstrations with real-world industrial wastewaters, expand the palette of catalysts and heterojunctions and include long horizon durability testing in dynamically variable weather and loading conditions. More sophisticated analytics, including real-time spectroscopy, by-product, and toxicity testing will be used to ensure full mineralization and environmental friendliness. At the modeling level, the interaction between kinetic

analysis and strong mediation and moderation models can help to understand how the properties of catalysts, irradiance, hydraulic factors and the chemistry of water interplay to influence the results.
Overall, photocatalytic nanomaterials can be considered a practical and sustainable solution to increase the industrial wastewater treatment, but this success depends on the responsible regulation of light intensity. Through aligning catalyst development with optical and reactor technology, it is possible to transform laboratory benefits to reliable, scalable technology that minimizes environmental hazard, minimizes sludge and energy expenditure and pioneer further development towards cleaner water infrastructure.

REFERENCES

Akram, N., Zubair, S. S., Asghar, F., Nishtar, Z., & Lodhi, K. (2023). Public-private partnerships (PPPs) in construction projects: A study on the utilization, effectiveness, and challenges in Pakistan. *Bulletin of Business and Economics (BBE)*, *12*(3), 402-409.

Akram, N., Farooq, P., Haq, M. U., Nabeel, M., & Asghar, F. (2024). Evaluating the Financial Feasibility of Renewable Energy Integration in Construction Sector. *The Asian Bulletin Of Green Management And Circular Economy*, *4*(1), 1-15.

Arshad, W., Akram, N., Kamal, A. S., ul Haq, M., Khurshid, A. M. M., & Qayyum, A. A. (2025). ECO-FRIENDLY CONCRETE: MERGING FLY ASH AND HEMP FOR GREEN BUILDING PRACTICES. *Spectrum of Engineering Sciences*, *3*(4), 1000-1019.

Akram, N., Mubin, S., Malik, A. M., Imran, R., & Jamil, M. (2024). Decoding the Interplay of Lighting and Spatial Dynamics: A Simulation-Based Case Study Analysis across Diverse Building Orientations. *Metallurgical and Materials Engineering*, *30*(4), 434-458.

Akram, N., Ashraf, M. Z., Jamil, M., Hasan, B., & ul Haq, M. (2025). GREEN CONCRETE: ENHANCING STRENGTH AND WORKABILITY FOR SUSTAINABLE CONSTRUCTION. *Kashf Journal of Multidisciplinary Research*, *2*(07), 87-120.

Akram, N., Mubin, S., Masood, R., Malik, A. M., Naeem, S., Gulzar, R., ... & Rashid, M. (2025). Beyond Illumination: Stakeholders Perspectives and Preferences on Eco-Friendly Lighting for Sustainable Cities. *Metallurgical and Materials Engineering*, *31*(1), 249-276.

Akram, N., ul Haq, M., Khalil, A., Zaman, L., Fahad, M., & Asghar, F. (2024). Shedding Light on Financial Sustainability: Data driven insights of the Economic Implications of Energy-Efficient Lighting in the Construction Industry. *The Asian Bulletin of Big Data Management*, *4*(02), 1-19.

Asif, M., Akram, N., Khurshid, M. M., Kaynat, A., Naeem, S., Malik, A. M., & ul Haq, M. (2025). Recycling Agricultural Waste for Green Concrete: The Case of Palm Oil Ash. *THE PROGRESS: A Journal of Multidisciplinary Studies*, *6*(3), 27-42.

Asghar, F., & Nabeel, M. (2025). The Impact of Perceived Risk on Behavioral Intention toward Mobile Banking in Pakistan: The Mediating Role of Digital Knowledge.

Akbar, U., Asghar, F., & Arshad, M. (2025). FinTech Disruption and Transformation in Banking: Mediating Effect of Artificial Intelligence. Advance Journal of Econometrics and Finance, 3(2), 210-223.

Badawi, A. K., Salama, R. S., & Mostafa, M. M. M. (2023). Natural-based coagulants/flocculants as sustainable market-valued products for industrial wastewater treatment: a review of recent developments. *RSC advances*, *13*(28), 19335-19355.

Bharti, S. (2025). Recent advances in heavy metal removal from wastewater using nanomaterials and cloud point extraction: A comprehensive review. *International Journal of Environmental Science and Technology*, *22*(6), 5057-5084.

Buzzetti, L., Crisenza, G. E., & Melchiorre, P. (2019). Mechanistic studies in photocatalysis. *Angewandte Chemie International Edition*, *58*(12), 3730-3747.

Chauhan, A., Sillu, D., & Agnihotri, S. (2019). Removal of pharmaceutical contaminants in wastewater using nanomaterials: a comprehensive review. *Current drug metabolism*, *20*(6), 483-505.

Coccia, M., & Bontempi, E. (2023). New trajectories of technologies for the removal of pollutants and emerging contaminants in the environment. *Environmental Research*, *229*, 115938.

Dong, S., Feng, J., Fan, M., Pi, Y., Hu, L., Han, X., ... & Sun, J. (2015). Recent developments in heterogeneous photocatalytic water treatment using visible light-responsive photocatalysts: a review. *Rsc Advances*, *5*(19), 14610-14630.

Giannetti, B. F., Agostinho, F., Eras, J. C., Yang, Z., & Almeida, C. M. V. B. (2020). Cleaner production for achieving the sustainable development goals. *Journal of Cleaner Production*, *271*, 122127.

Giovannetti, R., Rommozzi, E., Zannotti, M., & D'Amato, C. A. (2017). Recent advances in graphene based TiO2 nanocomposites (GTiO2Ns) for photocatalytic degradation of synthetic dyes. *Catalysts*, *7*(10), 305.

Guo, R., Tian, R., Shi, D., Li, H., & Liu, H. (2019). S-Doped ZnSnO3 nanoparticles with narrow band gaps for photocatalytic wastewater treatment. *ACS Applied Nano Materials*, *2*(12), 7755-7765.

Hoffmann, M. R., Martin, S. T., Choi, W., & Bahnemann, D. W. (1995). Environmental applications of semiconductor photocatalysis. *Chemical reviews*, *95*(1), 69-96.

Hussain, A., Kumari, R., Sachan, S. G., & Sachan, A. (2021). Biological wastewater treatment technology: Advancement and drawbacks. In *Microbial ecology of wastewater treatment plants* (pp. 175-192). Elsevier.

Ilyas, M., Ahmad, W., Khan, H., Yousaf, S., Yasir, M., & Khan, A. (2019). Environmental and health impacts of industrial wastewater effluents in Pakistan: a review. *Reviews on environmental health*, *34*(2), 171-186.

Jari, Y., Roche, N., Necibi, M. C., El Hajjaji, S., Dhiba, D., & Chehbouni, A. (2022). Emerging pollutants in Moroccan wastewater: occurrence, impact, and removal technologies. *Journal of Chemistry*, *2022*(1), 9727857.

Kumar, S., Kumar, A., Bahuguna, A., Sharma, V., & Krishnan, V. (2017). Two-dimensional carbon-based nanocomposites for photocatalytic energy generation and environmental remediation applications. *Beilstein journal of Nanotechnology*, *8*(1), 1571-1600.

Kusiak-Nejman, E., & Morawski, A. W. (2019). TiO2/graphene-based nanocomposites for water treatment: A brief overview of charge carrier transfer, antimicrobial and photocatalytic performance. *Applied Catalysis B: Environmental*, *253*, 179-186.

Khan, S. Z., Gul, M. S., & Asghar, F. (2025). The Role of Artificial Intelligence in Enhancing Financial Forecasting Accuracy. Advance Journal of Econometrics and Finance, 3(3), 166-174.

Li, J., Jing, Y., Xing, G., Liu, M., Cui, Y., Sun, H., ... & Li, A. (2022). Solar-driven interfacial evaporation for water treatment: advanced research progress and challenges. *Journal of Materials Chemistry A*, *10*(36), 18470-18489.

Majumder, S., Chatterjee, S., Basnet, P., & Mukherjee, J. (2020). ZnO based nanomaterials for photocatalytic degradation of aqueous pharmaceutical waste solutions–A contemporary review. *Environmental Nanotechnology, Monitoring & Management*, *14*, 100386.

Marcelino, R. B., & Amorim, C. C. (2019). Towards visible-light photocatalysis for environmental applications: band-gap engineering versus photons absorption—a review. *Environmental Science and Pollution Research*, *26*(5), 4155-4170.

Morin-Crini, N., Lichtfouse, E., Fourmentin, M., Ribeiro, A. R. L., Noutsopoulos, C., Mapelli, F., ... & Crini, G. (2022). Removal of emerging contaminants from wastewater using advanced treatments. A review. *Environmental Chemistry Letters*, *20*(2), 1333-1375.

Okereke, J. N., Ogidi, O. I., & Obasi, K. O. (2016). Environmental and health impact of industrial wastewater effluents in Nigeria-A Review. *Int J Adv Res Biol Sci*, *3*(6), 55-67.

Purabgola, A., Mayilswamy, N., & Kandasubramanian, B. (2022). Graphene-based TiO2 composites for photocatalysis & environmental remediation: synthesis and progress. *Environmental Science and Pollution Research*, *29*(22), 32305-32325.

Raj, A., & Tembhurkar, A. R. (2024). Evolution of photocatalysis process for degradation of residual xanthate in wastewater from mineral processing industry-A review. *Journal of Water Process Engineering*, *67*, 106130.

Rafiq, M., Asghar, F., Haider, S., Khan, H., & Bangash, S. A. (2024). THE INFLUENCE OF FINANCIAL TECHNOLOGY ON THE ECONOMIC CAPITAL EFFICACY CONCERNING BANKING RISK IN PAKISTAN, CONSIDERING THE MEDIATING FUNCTIONS OF COMPETITIVE DYNAMICS. Policy Research Journal, 2(4), 2074-2082.

Sansaniwal, S. K. (2022). Advances and challenges in solar-powered wastewater treatment technologies for sustainable development: a comprehensive review. *International Journal of Ambient Energy*, *43*(1), 958-991.

Sharma, S. S., Palaty, S., & John, A. K. (2021). Band gap modified zinc oxide nanoparticles: an efficient visible light active catalyst for wastewater treatment. *International Journal of Environmental Science and Technology*, *18*(9), 2619-2632.

Shokri, A., & Sanavi Fard, M. (2022). A critical review in the features and application of photocatalysts in wastewater treatment. *Chemical Papers*, *76*(9), 5309-5339.

Tak, S., Grewal, S., Shreya, Phogat, P., Manisha, Jha, R., & Singh, S. (2024). Mechanistic Insights and Emerging Trends in Photocatalytic Dye Degradation for Wastewater Treatment. *Chemical Engineering & Technology*, *47*(11), e202400142.

Teh, C. Y., Budiman, P. M., Shak, K. P. Y., & Wu, T. Y. (2016). Recent advancement of coagulation–flocculation and its application in wastewater treatment. *Industrial & Engineering Chemistry Research*, *55*(16), 4363-4389.

Thanh, P. N., Phung, V. D., & Nguyen, T. B. (2024). Recent advances and future trends in metal oxide photocatalysts for removal of pharmaceutical pollutants from wastewater: a comprehensive review. *Environmental Geochemistry and Health*, *46*(9), 364.

Tony, M. A. (2023). Solar concentration for green environmental remediation opportunity—international review: advances, constraints and their practice in wastewater treatment. *International Journal of Environmental Analytical Chemistry*, *103*(11), 2568-2600.

Xiao, H., Li, K., Zhang, D., Tang, Z., Niu, X., Yi, L., ... & Fu, M. (2022). Environmental, energy, and economic impact assessment of sludge management alternatives based on incineration. *Journal of Environmental Management*, *321*, 115848.

Yang, Z., Zhou, S., Feng, X., Wang, N., Ola, O., & Zhu, Y. (2023). Recent progress in multifunctional graphene-based nanocomposites for photocatalysis and electrocatalysis application. *Nanomaterials*, *13*(13), 2028.

Yasser, F., & Asghar, F. (2024). Determinants of Money Demand by Business Sector for Extending Monetary Policy Applications in Pakistan. The Regional Tribune, 3(1), 213-224.