



# Article Unlocking the Potential of N-Doped SnO<sub>2</sub> for Sustainable Photocatalytic Degradation of Carcinogenic Dyes

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Abstract: Environmental adulteration is an emerging concern due to the discharge of wastewater effluents from several sources. Several carcinogenic dyes are the major contaminants in these water bodies. These could cause long-lasting and detrimental effects to humans as well as aquatic ecosystems. For efficient degradation of such dyes, the exploration of nanotechnology has demonstrated huge potential. Herein, the degradation of dyes (MB, CV, and MO) has been carried out photocatalytically using N-doped SnO<sub>2</sub> nanoparticles (N:SnO<sub>2</sub> NPs) as well as in presence of a sacrificial agent, EDTA. These NPs were synthesized at an ambient temperature. Different characterization techniques were used throughout the analysis of the synthesized NPs. The PXRD analysis reveals formation of single-phase rutile structure with tetragonal symmetry. Using the Scherrer formula, the size of the NPs was found to be less than 5 nm, exhibiting increases in size with N doping. Further, morphological analysis through field emission scanning electron microscopy (FESEM) and transmission electron microscopy (TEM) examined the existence of highly agglomerated, spherical NPs. The thermogravimetric analysis (TGA) results depict the thermal stability of the synthesized NPs up to a temperature of 800 °C. These synthesized N:SnO<sub>2</sub> NPs exhibit potent efficiency for the photocatalytic degradation of MB, MO, and CV dyes with an efficiency of 93%, 83%, and 73% degradation, respectively, under UV light irradiation. Additionally, the effect of the sacrificial agent, EDTA, was observed on the degradation process and resulted in a degradation of ~90% MB dye, 88% CV dye, and 86% MO dye within 15 min of UV light irradiation.

**Keywords:** tin dioxide; nanoparticles; photocatalyst; doping; methylene blue; crystal violet; methyl orange

# 1. Introduction

Rapid industrialization and increasing urbanization in the 21st century are emerging concerns regarding environmental pollution [1]. For researchers and professionals working in the field of environmental pollutants and especially water contaminants, the critical challenge lies in effectively removing wastewater that contains carcinogenic effluents from ground water [2,3]. Adjacently, wastewater purification with conventional methods is leading to an energy crisis across the globe. Current advancements in science opt for newer chemicals to be used in various industries, and these are organic dyes which are used in a



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**Copyright:** © 2023 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (https:// creativecommons.org/licenses/by/ 4.0/). number of industries, such as the fabric and leather industries [3–5]. Compared to other contaminants present in water, dyes have been recognized as the most easily recognizable pollutants owing to their color visibility in ever lower concentrations of 1 ppm [6]. It has been reported that industrial dying stuffs are the major contributors of toxic organic pollutants contaminating water [7]. Acidic and reactive dyes, being water soluble, are the most difficult to handle. Reactive dyes are rarely preferred for the dying of fabrication, owing to the problem that the remaining effluent is directly discharged into the water [8]. When these dyes are not ionized into water, they tend to bioaccumulate with aquatic life [9]. The main concern with dye effluents is their synthesis using carcinogenic aromatic compounds. The literature proposes a number of methods adopted for water purification that are associated with one or more limitation [2,10,11]. Taking the very simple and easiest method of adsorption, the adsorbent still carries the adsorbate on its surface, and hence needs to be disposed of again, leading to pollution [12]. Here, in this work, one of the most efficient processes has been used for the elimination of carcinogenic dyes from water: photocatalysis [13]. This method produces no secondary contaminants but itself degrades the primary contaminants into less toxic substances [14].

The elimination of carcinogenic dyes from water has been the subject of numerous investigations in the literature. After conducting a thorough literature survey, it was found that while there were few articles related to the synthesis of N-doped SnO<sub>2</sub> nanoparticles (N:SnO<sub>2</sub> NPs) and their characterization, there is a lack of literature available for removing dyes from water. However, a number of SnO<sub>2</sub>-based nanocomposites have been reported for photocatalytic dye degradation. Xu et al. compared the photocatalytic degradation of RhB dye with TiO<sub>2</sub>, SnO<sub>2</sub>, N-TiO<sub>2</sub>, and N-TiO<sub>2</sub>/SnO<sub>2</sub> and explained that the highest degradation was observed with N-TiO<sub>2</sub>/SnO<sub>2</sub>. The composite completely degraded the dye within 300 min of light irradiation [15,16]. Chen et al. used hydrothermally synthesized quantum dots modified with a N:SnO<sub>2</sub> composite to degrade RhB dye. It enhances the performance from 20% to 99% for RhB dye compared to pure  $SnO_2$  within 120 min [17]. N:SnO<sub>2</sub> nano-powder crystals were produced by Liu et al. via a solid-phase reaction technique that involved the utilizing of a surfactant, i.e., sodium *p*-toluene sulfonate (STS), and the process was performed at room temperature. The results showed enhanced degradation capacity of rice straw powder treatment wastewater (RSPTW), which occurs due to the formation of free radicals because of a low calcination temperature [18]. These studies demonstrate the potential of N:SnO<sub>2</sub> NPs as photocatalysts for dye degradation, and suggest that further research on N:SnO<sub>2</sub> NPs could lead to the development of more efficient and effective methods for the elimination of aqueous dyes.

Furthermore, the previously synthesized N:SnO<sub>2</sub> NPs via a novel solution-based method have been reported for their application in dihydrogen production. To explore other possibilities, the photocatalytic performance of the N:SnO<sub>2</sub> NPs for dye degradation has been studied in the present work. Given the preceding discussion, it was thought worthwhile to investigate the potential of N:SnO<sub>2</sub> NPs in photocatalytic dye degradation. N:SnO<sub>2</sub> NPs offer immense utilization among various domains, especially in the context of sustainable sources. Hence, in this work, a facile and novel solution-based synthesis of N:SnO<sub>2</sub> NPs at room temperature was carried out as previously described by Bhawna et al. [19]. These NPs have been explored as efficient photocatalysts for the decomposition of methylene blue (MB), methyl orange (MO), and crystal violet (CV) dyes when exposed to UV light.

Overall, this research could open up new avenues for environmental-associated concerns by providing an efficient and sustainable method for the degradation of carcinogenic dyes from water. The use of N:SnO<sub>2</sub> NPs as photocatalysts offers a potential solution to the environment problems associated with water pollution caused by industrial dyes. Moreover, the synthesis of N:SnO<sub>2</sub> NPs at room temperature through the simple and efficient solution-based method described in our study offers immense potential for various sustainable applications beyond the realm of dye degradation. For instance, these NPs could be utilized as a photocatalyst for hydrogen production, as previously reported by Bhawna et al. [19]. The use of sustainable materials and processes is crucial for addressing environmental challenges, and the development of such technologies can have far-reaching implications for industries and communities worldwide.

In the future, this research can pave the way for the development of more efficient and environmentally sustainable methods to manage wastewater and other forms of environmental industrialization, which have become pressing concerns in the present century. Our research output can encourage further exploration and innovation in the field of sustainable environmental solutions.

## 2. Experimental

# 2.1. Materials and Methods

All chemicals were of a high purity >99.9%; SnCl<sub>2</sub>•2H<sub>2</sub>O (tin (II) chloride dihydrate; Merck Chemicals, Rahway, NJ, USA), CH<sub>3</sub>OH (methanol; Merck Chemicals, Rahway, NJ, USA), H<sub>2</sub>O<sub>2</sub> (hydrogen peroxide; Qualigens, Thermo Fisher Scientific India Pvt. Ltd., Maharashtra, India).

# 2.2. Synthesis of N-Doped SnO<sub>2</sub> Nanoparticles

The N:SnO<sub>2</sub> NPs were prepared as described by Bhawna et al. [19]. In brief, a 0.5 M SnCl<sub>2</sub>•2H<sub>2</sub>O (Merck) solution was prepared in methanol and was diluted with 60 mL of methanol. Further, it was continuously stirred with 40 mL of hydrazine hydrate (Fisher Scientific Ltd., Waltham, MA, USA) and left at room temperature for 4 h. The pale, yellow-colored substance was then centrifuged, washed in methanol, and dried at 60 °C.

## 2.3. Characterization Studies

The powder X-ray diffraction (PXRD) patterns of the prepared N:SnO<sub>2</sub> NPs were carried out using a high-resolution D8 Discover Bruker X-ray diffractometer with radiation of Cu K $\alpha$  at wavelength 1.5418 Å; the operating voltage is 40 kV, and the 15 mA current is applied. The prepared sample was coated onto the glass substrate, and the XRD patterns were recorded at 20 from 5° to 80° with a scanning speed of 1°/min and scanning steps of 0.02°/min. The morphology of the N:SnO<sub>2</sub> NPs were demonstrated using a Zeiss GeminiSEM 500 Thermal field emission-type FESEM with a scanning voltage of 0.02–30 kV. Moreover, to gather a detailed understanding of the N:SnO<sub>2</sub> NPs, transmission electron microscopy (TEM) using TEM-JEOL 2100F was carried out. Thermogravimetric analysis (TGA) was also performed on HiRes1000 RT up to 1100C to determine the thermal stability with a continuous flow of nitrogen at a heating rate of 10 °C/min.

## 2.4. Photocatalytic Dye Degradation Performance

The photocatalytic performance of the N:SnO<sub>2</sub> NPs was evaluated in terms of degradation of MB, MO, and CV dyes when exposed to UV light and also in the presence of EDTA as a sacrificial agent. The reaction beaker was positioned on a magnetic stirrer, which had an aperture at the top for the purpose of exposure to UV light irradiation. Briefly, a quantity of 0.1 g of catalyst was added to 100 mL of dye solution with a concentration of  $20 \times 10^{-6}$  M. In total, 10 mL of the reference standard was centrifuged and collected. The solution was stirred continuously for 30 min under dark conditions to ensure that an adsorption–desorption equilibrium between the dye and the catalyst was reached. After dark reaction, 10 mL of the solution was centrifuged and collected. The UV light lamp was switched on for the light reaction. Subsequently, the solution was exposed to UV light. At 15 min intervals, a specific volume of 10 mL of the sample was taken and centrifuged, and the concentration of the sample was measured using UV-Vis spectroscopy. Similar steps were followed with the CV and MO dyes. The experiments were also performed by adding a drop of 3 mM EDTA into the dye solution to observe the effect of the sacrificial agent on the degradation process. The rate of MB, MO, and CV dye degradation under UV light radiation as well as the absorbance of the collected samples was measured at  $\lambda_{max}$ , and the degradation rate was calculated using the following formula:

Dye degradation efficiency (%) = 
$$\frac{C_0 - C_t}{C_0} \times 100$$

where  $C_0$  represents the initial concentration and  $C_t$  represents the final concentration at time *t*. The term "time" (*t*) refers to the amount of time needed for the catalyst to degrade 50% of the dye in an aqueous solution.

# 3. Results and Discussion

## 3.1. Powder XRD Analysis

Figure 1 illustrates the diffraction pattern of the N:SnO<sub>2</sub> NPs fabricated via a facile chemical approach at room temperature. The figure demonstrates the rutile structure of the nanoparticles, with crystal lattice parameters presented in Table S1, along with space group P4<sub>2</sub>/mnm and tetragonal symmetry. The diffraction peaks at different theta (2 $\theta$ ) values demonstrate a clear mirroring of the crystallographic planes (110), (101), (200), (211), (220), (002), (310), and (221), respectively. Further, this corresponds to JCPDS file number 41-1445 [20–25]. Apart from the abovementioned diffraction peaks, no other intense peak was observed, thus indicating the high purity of the N:SnO<sub>2</sub> NPs. Additionally, it can be elucidated that the observed diffraction peaks overlap the standard characteristic peak positions of the SnO<sub>2</sub> NPs, which confirms a single-phase synthesis of the desired N:SnO<sub>2</sub> NPs prepared using the solution-based synthesis.



Figure 1. The PXRD pattern of the N:SnO<sub>2</sub> nanoparticles.

The Scherrer formula was used to determine the average crystalline size of the N:SnO<sub>2</sub> NPs, as shown below:

$$D = \frac{k\lambda}{\beta cos\theta}$$

where *D* represents the crystallite size, *k* is a constant equivalent to 0.9,  $\lambda$  is the wavelength of the X-ray,  $\beta$  is the full width at half maximum (FWHM), and  $\theta$  is Bragg's diffraction

angle. The diffraction that was picked to calculate the crystalline size is the intensity peak at  $d_{211}$ . From this, the calculated size of the crystallite was found to be 3.4 nm, whilst the crystalline size of the pure SnO<sub>2</sub> NPs was found to be 0.6 nm. Therefore, the size of the crystallite illustrates that the size of the N:SnO<sub>2</sub> increases with the doping of N.

The Williamson–Hall (W–H) method is a popularly used approach to evaluate the lattice strain and the crystalline size of the desired material. It does so by investigating the broadness of the PXRD peaks that occurs due to intrinsic strain. As it takes into account the microstrain as well as the crystalline size of the material, it is thus beneficial for interpreting the overall broadening of the XRD peak [26,27]. The equation used to calculate the W–H plot using the following equation is as follows:

$$eta_{Total}=eta_{Strain}+eta_{Crystalline\;Size}$$

Herein,  $\beta_{Strain} = \varepsilon \times 4tan\theta$  and  $\beta_{Crystalline Size} = \frac{k\lambda}{Dcos\theta}$ . Therefore, upon substituting  $\beta_{strain}$  and  $\beta_{crystalline size}$  to the above equation:

$$\beta_{Total} = \varepsilon \times 4tan\theta + \frac{k\lambda}{D\cos\theta}$$
$$\beta_{Total} \times \cos\theta = \varepsilon \times 4sin\theta + \frac{k\lambda}{D}$$

where,  $\varepsilon$  represents the intrinsic strain and  $\lambda$  is the wavelength of the X-ray beam, i.e., equivalent to 0.154 nm. After performing the linear fitting, the W–H plot is illustrated in Figure 2.



Figure 2. The W–H plot of the N:SnO<sub>2</sub> nanoparticles.

From the graph, the intrinsic strain and average size of the crystallite was enumerated to be approximately  $-7.56 \times 10^{-3}$  and 4.3 nm, respectively. The expansion of the lattice overserved in the W–H plot can be attributed to an increase in the size of the crystalline structure in the N:SnO<sub>2</sub> NPs, as indicated by the negative slope. This confinement can cause the atoms within the crystal to be arranged differently than they would be in their bulk counterpart, resulting in lattice expansion [19].

The morphological identification of N:SnO<sub>2</sub> NPs was exhibited via FESEM analysis (Figure 3) and TEM (Figure 4). FESEM imaging reveals the formation of uniformly distributed spherical NPs. However, there is high agglomeration of the NPs, which is common in NM synthesis. As can be seen from Figure 3A, the distribution of the particles is completely uniform. The corresponding micrographs for elemental mapping of the NPs are shown in Figure 3C. The distribution of elements in the mapping micrographs has been demonstrated with different colors, such as yellow, representing Sn, red for N, and green for O. The elemental distribution in the mapping micrographs endorses the formation of N:SnO<sub>2</sub> NPs. In our previous report, the concentration of N ions incorporated into the tin lattice using X-ray photoelectron spectroscopy (XPS) was found to be 4.6% [19].



Figure 3. (A) FESEM micrograph, (B) EDAX, and (C) elemental mapping of N:SnO<sub>2</sub> nanoparticles.



Figure 4. TEM image of (A) crystal lattice fringe, and (B) SAED pattern of N:SnO<sub>2</sub> nanoparticles.

Additionally, the TEM image provides a detailed view of the morphology of the synthesized NPs. The image shows that the NPs are well-dispersed, and the size of the NPs size appears to be consistent with the size calculated using the Debye–Scherrer formula in the XRD analysis. Spherical-shaped NPs with a particle size smaller than 5 nm were formed, which is confirmed via the TEM images shown in Figure 4 and is consistent with the FESEM results. The crystal lattice fringe spacings of 0.329 nm are for the (110) plane, as shown in Figure 4A [28]. Furthermore, the highly crystalline structure of SnO<sub>2</sub> is indicated through the selected area electron diffraction (SAED), as shown in Figure 4B. The diffraction circles from small to large represent (110), (101), and (211) planes of rutile-structured SnO<sub>2</sub>, respectively, in agreement with the XRD data. This clearly indicates that the synthesized N:SnO<sub>2</sub> NPs are highly crystalline and possess a well-defined structure.

The highly crystalline nature of the synthesized N:SnO<sub>2</sub> NPs is of great importance for their photocatalytic application [29–31]. This allows for efficient charge transfer to occur, resulting in an enhancement of the photocatalytic activity of the NPs. The observed crystal lattice fringe spacings and the SAED pattern confirm the good quality of the synthesized N:SnO<sub>2</sub> NPs and suggest their potential use as highly efficient photocatalysts.

## 3.3. TGA Analysis

TGA analysis is a frequently employed method used to study the thermal endurance of substances. In the case of N:SnO<sub>2</sub> NP photocatalysts, the TGA curve demonstrated in Figure 5 illustrates the weight loss of the sample as a function of temperature. The curve shows two weight loss regions, one below 200 °C and the other between 200 °C to 800 °C. Firstly, an evident 7% weight loss was observed at temperatures below 200 °C [32]. This weight change observed in the photocatalyst was caused by the removal of adsorbed water and gases from its surface. Additionally, a 7% weight loss was observed within the temperature range of 200 °C to 800 °C, indicating that other substances in the photocatalyst were being eliminated. This could be due to the decomposition of organic compounds or other volatile species that may have been present in the sample. The rate of weight loss in this region was slower than the first region, indicating that the decomposition process was slower. However, no significant change in weight was noticed above 800 °C, suggesting that the photocatalyst remained stable at high temperatures due to its inorganic composition of SnO<sub>2</sub>. Therefore, it is recommended to set the calcination temperature for N:SnO<sub>2</sub> NPs to 800 °C to maintain the catalyst's stability. It is important to note that more details about the experiment are required to fully understand the context of these observations. For example, the heating rate, sample mass, and atmosphere during the TGA analysis can all influence the results. Nevertheless, the TGA curve offers significant insights into the N:SnO<sub>2</sub> photocatalyst's thermal stability and can be used to optimize the calcination temperature for the synthesis of the material.

#### 3.4. Surface Area Analysis

The N<sub>2</sub> adsorption/desorption isotherm of the N:SnO<sub>2</sub> NPs at 77 K has been presented in our previous published paper. The Barrett–Joyner–Halenda (BJH) method revealed the pore volume, pore size, and specific surface area to be 13.59 cc/g, 3.82 nm, and 139.7 m<sup>2</sup>/g, respectively. At relative pressures between 0.3–1.0, the adsorption/desorption graph (Figure 6) displays a type IV isotherm with an H3 hysteresis loop, which is evidence of mesoporosity [19].



Figure 5. TGA curve of N:SnO<sub>2</sub> nanoparticles.



Figure 6. Barrett–Joyner–Halenda graph of N:SnO<sub>2</sub> nanoparticles.

# 3.5. Photocatalytic Activity of Carcinogenic Dyes

Photocatalytic dye degradation of MB, MO, and CV in aqueous solution was carried out using N:SnO<sub>2</sub> NPs under UV light irradiation. Nevertheless, the degradation efficiency of these dyes using N:SnO<sub>2</sub> NPs was also investigated in the presence of EDTA as sacrificial agent when exposed to UV light irradiation. The pure SnO<sub>2</sub> NPs do not exhibit any photodegradation ability for any of the mentioned aqueous dye solution. The results demonstrated less than 10% degradation of the reported dyes in the aqueous solutions, even after 90 min of irradiation under UV light. The incorporation of N to the surface of  $SnO_2$  greatly improved the activity of the desired N:SnO<sub>2</sub> NPs. Figure 7 illustrates the UV-Vis absorption of the reported dyes over time during exposure to UV light. It can be observed distinctly that the absorbance decreased exceptionally after irradiation within a maximum of 90 min for the N:SnO<sub>2</sub> NP photocatalyst. Figure S1 illustrates the photocatalytic degradation of the MB dye as a function of the irradiation time for the N:SnO<sub>2</sub> NPs. In Figure S2 the bottle numbered with '0' contains the standard solution, and the one numbered with '1' contains the solution after 30 min. Stirring of the dye with the sample was conducted in the dark, and further samples were collected at intervals of 15 min. The analysis showed that the performance of the N:SnO<sub>2</sub> NPs improves up to 50 min, and then declines as the photo-reduction time increases up to 70 min. The photodegradation efficiency of MB could reach up to 93% during an irradiation time of 75 min. Similarly, Figure S3 depicts the photodegradation of the MO dye. It is observed that the performance of the N:SnO<sub>2</sub> NPs increases during up to 90 min of photo-reduction time. The degradation efficiency of MO could reach up to 84% over 90 min. Likewise, Figures S4 and S5 uncloaked the photodegradation of the CV dye. It can be elucidated that the photocatalytic ability of the N:SnO<sub>2</sub> NPs increases during the first 30 min and then decreases until 75 min of photo-reduction time has elapsed. The degradation efficiency of CV could reach up to 73% in 90 min. However, the pure  $SnO_2$  NPs were only capable of decomposing small quantities of the respective dyes. Notably, the photocatalytic test was repeated more than twice under the same experimental set-up to assess the photodegradation ability of the N:SnO<sub>2</sub> NPs. Thus, the derived results evinced that N:SnO<sub>2</sub> NPs exhibited improved photocatalysis in the degradation of carcinogenic dye solutions.



**Figure 7.** Photocatalytic degradation of Methylene Blue (MB), Methyl Orange (MO), and Crystal Violet (CV) dyes independently and along with EDTA as a sacrificial agent.

The photocatalytic degradation of various dyes was also performed using synthesized NPs along with EDTA as a sacrificial reagent (Figure 7). The results show that with EDTA,

N:SnO<sub>2</sub> degraded ~90% of the MB dye, 88% of the CV dye, and 86% of the MO dye within 15 min of UV light irradiation. This enhanced degradation performance owes to the hole, superoxide  $(O_2^{-\bullet})$  radical, and hydroxyl (•OH) radical. EDTA restricted the recombination of electron–hole pairs by capturing the holes [33], and hence resulted in better degradation as compared to those where no EDTA was used.

After successful catalysis, the stability of the used N:SnO<sub>2</sub> NPs was further assessed. To do so, the PXRD pattern of the after-reaction photocatalyst was plotted as shown in Figure S6. As clearly illustrated, the observed crystallographic peaks correspond exactly with the SnO<sub>2</sub> tetragonal phase. Furthermore, no diminished, weakened, or unwanted reflections of diffraction peaks were identified, thus indicating the durability and integrity of the N:SnO<sub>2</sub> NPs.

## 3.6. Photocatalytic Mechanism of Dye Degradation

To comprehend the likely mechanism of photocatalysis of carcinogenic dyes such as MB, MO, and CV by N:SnO<sub>2</sub> NPs and determine a definitive insight on the same, the band gap position of the synthesized N:SnO<sub>2</sub> NPs catalyst must be unraveled. This is due to the aspects of photo-excited electrons and holes mediating excitation, transport, and recombination. In the previous study conducted by Bhawna et al., the band gap assessment was conducted and the conduction band (CB) and the valence band (VB) edge positions of the N:SnO<sub>2</sub> NPs was theoretically computed to be -1.13 eV and 2.32 eV, respectively [19]. The band gap of  $SnO_2$  in its pure form is 3.6 eV, as reported in the literature [2]. However, when doped with N, N:SnO<sub>2</sub> now possesses a modified band gap of 3.45 eV, as calculated in our previous research using a UV-Visible spectrum [5,19]. This shift in band gap has been explained as a result of an N substitution in the SnO<sub>2</sub> crystal structure and the overlap of O (2p) and N (2p) orbitals. The FTIR data from our previous research article state that doping substitutes the O atom into a tin lattice with an N atom, resulting in lattice oxygen vacancies which are responsible for the photocatalytic performance of N:SnO<sub>2</sub> NPs [19]. The possible mechanism of photocatalysis of N:SnO<sub>2</sub> NPs was schematically represented in Figure 8.

Figure 8 illustrates the likely mechanism for the breakdown of MB, MO, and CV dyes using N:SnO<sub>2</sub> NPs. When the photocatalyst is exposed to light irradiation, electrons in the VB were stimulated into the CB. These electrons move to the catalyst's surface to contribute to surface reactions. Oxygen molecules adsorbed or dissolved in water react with the electrons at the surface, leading to the formation of  $O_2^{-\bullet}$ . Additionally, •OH is created when holes in the VB interact with water molecules or OH ions.

The  $O_2^{-\bullet}$  and  $\bullet$ OH are highly reactive oxidizing agents that can react with organic dyes. These agents attack the dye molecules, leading to their oxidative breakdown and the production of less toxic compounds. The degradation efficiency of N:SnO<sub>2</sub> NPs has been attributed to the lattice disorder and charge imbalance created in the tin lattice on incorporation of N ions. The presence of N ions enhances the separation of photo-excited electron–hole pairs and increases the number of active sites for photocatalysis, resulting in the improved photocatalytic activity of the N:SnO<sub>2</sub> NPs.

Overall, the mechanism shown in Figure 8 provides insights into the working principle behind the degradation of organic dyes utilizing N:SnO<sub>2</sub> NPs and highlights the importance of charge separation and active sites for efficient photocatalytic activity.



Figure 8. Illustration demonstrating the photocatalytic mechanism of N:SnO<sub>2</sub> nanoparticles.

## 4. Conclusions

In this report, we have successfully synthesized N:SnO<sub>2</sub> NPs using a one-step facile synthetic strategy and investigated their potential as a photocatalyst for carcinogenic dye degradation. The structural and morphological studies of N:SnO<sub>2</sub> NPs were confirmed, demonstrating their uniform size distribution and crystalline nature, through several characterization tools such as PXRD, FESEM, TGA, and others. The synthesized N:SnO<sub>2</sub> NPs have been explored as excellent photocatalysts that could efficiently degrade up to 93% of the MB dye, 83% of the MO dye, and 73% of the CV dye under UV light irradiation. Additionally, the role of EDTA as a sacrificial agent was also investigated for these dyes. It can be elucidated that ~90% of these dyes degraded within 15 min when exposed to UV light and exhibited the potent efficiency of the synthesized NPs.

Future studies could investigate the underlying mechanism and role of sacrificial agents responsible for the high photocatalytic efficiency for degradation of N:SnO<sub>2</sub> NPs. The efficiency and simplicity of the one-step synthesis method for N:SnO<sub>2</sub> NPs make them an attractive candidate for use in various industries and research fields. Therefore, the findings of this study could have a considerable influence on the advancement of sustainable and eco-friendly technologies for wastewater treatment and pollution control.

**Supplementary Materials:** The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/separations10060322/s1, Figure S1: temporal absorption spectrum changes of methylene blue (MB) aqueous solution in the presence of N:SnO<sub>2</sub> NPs under UV light irradiation; Figure S2: color disappearance of MB aqueous solution in the presence of N:SnO<sub>2</sub> NPs under UV light irradiation; Figure S3: the temporal absorption spectrum changes of methyl orange (MO) aqueous solution in the presence of N:SnO<sub>2</sub> NPs under UV light irradiation; Figure S4: the temporal absorption spectrum changes of crystal violet (CV) aqueous solution in the presence of N:SnO<sub>2</sub> NPs under UV light irradiation; Figure S5: color disappearance of CV aqueous solution in the presence of N:SnO<sub>2</sub> NPs under UV light irradiation; Figure S5: color disappearance of CV aqueous solution in the presence of N:SnO<sub>2</sub> NPs under UV light irradiation; Figure S5: color disappearance of CV aqueous solution in the presence of N:SnO<sub>2</sub> NPs under UV light irradiation; Figure S5: color disappearance of CV aqueous solution in the presence of N:SnO<sub>2</sub> NPs under UV light irradiation; Figure S5: color disappearance of CV aqueous solution in the presence of N:SnO<sub>2</sub> NPs under UV light irradiation; Figure S5: color disappearance of CV aqueous solution in the presence of N:SnO<sub>2</sub> NPs under UV light irradiation; Figure S5: color disappearance of CV aqueous solution in the presence of N:SnO<sub>2</sub> NPs under UV light irradiation; Figure S6: comparative PXRD pattern of

N:SnO<sub>2</sub> nanoparticles: before (black) and after (red) catalysis; Table S1: calculation of parameters of N:SnO<sub>2</sub> nanoparticles.

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