AQUA
Water Infrastructure, Ecosystems and Society

AQUA — Water Infrastructure, Ecosystems and Society Vol 71 No 12, 1344 doi: 10.2166/aqua.2022.218

Niobium pentaoxide (Nb_2O_5) as an efficient photocatalyst for photocatalytic degradation of rhodamine-B

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ABSTRACT

One of the most important problems that the world is currently facing in terms of its impact on the environment is figuring out how to properly manage textile effluents. Photocatalysis has been shown to be successful in the removal of intractable chemicals and is regarded as a viable wastewater treatment technology. This work focused on the photocatalytic degradation of rhodamine-B (RB) in an aqueous solution, as well as the photocatalytic behavior of niobium pentaoxide (Nb_2O_5) as a photocatalyst was tested. It is important to note that good photocatalytic efficiency is highly dependent on the operating conditions. There are several process parameters that influence RB photocatalytic degradation, including the amount of photocatalyst (Nb_2O_5) used, the concentration of RB at the start of the reaction, and the pH of the solution optimized under visible-light irradiation. According to the findings, the conditions in which the greatest amount of RB was degraded were those in which the concentration of the catalyst was 10 mg/l, the dosage of the catalyst was 1 mg/l, and the pH was 11. The results also revealed that after utilizing the catalyst three times in a row, catalyst efficiency was maintained, and the degradation rate was maintained at a greater level.

Key words: degradation, Nb_2O_5, photocatalysis, rhodamine-B, visible-light irradiation

HIGHLIGHTS

- Photocatalytic degradation of rhodamine-B (RB) using niobium pentaoxide (Nb_2O_5) as a photocatalyst was tested.
- Effects of different process parameters have been studied.
- The result shows that the maximum degradation of RB was observed at 10 mg/l RB concentration, 1 mg/l catalyst (Nb_2O_5) dose, and the pH was 11.
- This work will provide some context and guidelines for those who are new to the field of photocatalytic degradation of RB.

INTRODUCTION

Dyes are widely used in the fabric/textile industry so major sources of environmental pollution are dye wastewater pollutants (Al-Kahtani 2017). Fabric/textile industry wastewater produced intensive organic dyes and the toxicity of these dyes has become a worldwide problem for the aquatic system (Ucker *et al.* 2021). The greater durability of modern synthetic dyes with their complicated aromatic structure makes biological treatment approaches ineffective (Yang *et al.* 2012). For the treatment of dye wastewater, currently some other physical and chemical techniques such as coagulation, ultra-filtration, adsorption, and membrane separation are available with limited success (Prado *et al.* 2008; Zhang *et al.* 2008; Qamar & Muneer 2009). Rhodamine-B (RB), one of the most important dyes, is used in many industrial processes for dyeing paper and producing a dye laser (Liang & Guo 2010; Topare *et al.* 2015). It has been experimentally proven that RB is harmful to animals and human beings which causes respiratory tract, irritation of the eyes, and skin. Thus, keeping the harmful effects and hazardous nature of RB, it was measured important to make efficient efforts to degrade RB from an aqueous solution (Akpan & Hameed 2009; Zhou *et al.* 2011).

The use of advanced oxidation processes (AOPs), in the degradation of the organic pollutants using the photocatalyst, has shown the potential to completely remove the organic and inorganic pollutants apart from the other major technologies available which concentrate the dye on an adsorbent that involves the transfer of the pollutant from a liquid phase to another phase (Kaviyarasu *et al.* 2013; Fairooz & Ali 2016; Santos *et al.* 2019). The material's photocatalytic activity and other properties are significantly affected by its crystalline structure (Nunes *et al.* 2020). In addition, it is common knowledge that the synthesis pathway approach possibly prominent role in determining the structural properties that are ultimately produced (Prado *et al.* 2021).

The photodegradation of pollutants may benefit from the implementation of an innovative new approach, which makes use of the Nb_2O_5 catalyst. This approach can be applied to a wide variety of semiconductors; in particular, metal oxide semiconductors have high surface areas and unique optical and electrical properties that make them ideal for use in photocatalytic applications. Thermodynamically stable and highly corrosion-resistant, niobium pentoxide (Nb_2O_5) has the potential to be used as a catalytic oxidation catalyst for organic molecules in aqueous conditions (Hashemzadeh *et al.* 2013; Osman *et al.* 2021). Nb_2O_5 has strong corrosion resistance and low toxicity, which has piqued the interest of the research community. This compound has a wide range of uses, including catalysis, solar cells, gas sensors, and electrochromic, to name a few. It has also been the subject of some recent studies (Brites *et al.* 2011; Carvalho *et al.* 2020). Dehydration, hydration, etherification, hydrolysis, condensation, alkylation, dehydrogenation, and oxidation are only a few of the many processes for which Nb_2O_5 is utilized as a catalyst (Topare *et al.* 2013; Jesus *et al.* 2021).

Visible-light irradiation photocatalyst development and comparison of photocatalytic activity of various photocatalysts for dye degradation have been the subject of substantial research in recent years (Moreira & Borges 2018). One of the prospective photocatalysts, Nb_2O_5, which has a band gap energy of 3.4 eV and is comparable to that of TiO_2, demonstrates strong photocatalytic activity in the process of dye photodegradation (Reeta *et al.* 2018). This makes it one of the most promising photocatalysts. The use of Nb_2O_5 for the photodegradation of pollutants, on the other hand, is not widely investigated in the published research (Paris *et al.* 2020; Troncoso & Tonetto 2021). In the present study, Nb_2O_5 was used as a photocatalyst and the photocatalytic activity of this material on RB dye was investigated when it was exposed to visible light. To determine the optimal conditions for photocatalytic degradation of RB, the study examined how several parameters, including the starting concentration of RB, the dosage of the catalyst (Nb_2O_5), and the pH of the solution, impacted the process.

MATERIALS AND METHODS

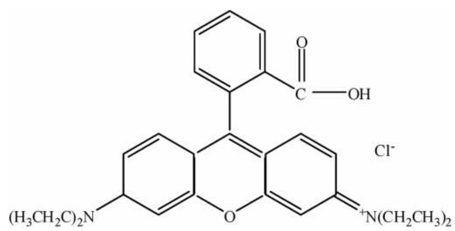
Materials

RB is widely used in dyeing the fabric used for experimental work. The molecular formula of RB is $C_{28}H_{31}ClN_2O_3$ and has a molar mass of 479.02. RB dye chemical structure is given in Table 1. The photocatalyst was used as the analytic grade of Nb_2O_5 (99.9%). Various reagent solutions were made up in double-distilled water for the experiments. To control the acidity and alkalinity of the solutions, 0.1 N HCl/0.1 N NaOH was utilized.

System requirements (photocatalytic reactor)

The specially designed batch reactor was used to carry out photocatalytic degradation as shown in Figure 1. The reactor consists of cylindrical vessels having a diameter of 70 mm and a length of 330 mm with the condensation system. It also consists

Table 1 | RB chemical structure

Name of dye	Chemical structure
Rhodamine-B (RB)	

of the inside tube having a diameter of 30 mm and a length of 330 mm with a closing cap of a diameter of 335 mm. The batch reactor material of construction is quartz.

Methods

The fixed amount of photocatalyst Nb_2O_5 was added to 250 ml of 30 ppm RB solution in each run at a specific pH in the degradation experimental study. The solution was starring for a set interval of time with help of a magnetic stirrer visible-light irradiation. The material was pipetted out at regular intervals and then separated using centrifugation to isolate the catalyst. The percentage of degradation yield of RB was calculated as follows (Akpan & Hameed 2009):

$$\text{Percentage degradation} = [(X_0 - X_i)/X_0] \times 100 \quad (1)$$

where X_0 is the RB initial concentration and X_i is the RB concentration after photo-irradiation. Figure 2 shows the photocatalytic degradation experimental setup.

RESULTS AND DISCUSSION

Impact of the various process parameters

The experiments were carried out by employing Nb_2O_5 as a photocatalyst onto RB when exposed to visible light. The degradation efficiency was evaluated by the influence of process parameters including catalyst (Nb_2O_5) dosage (0.25, 0.5, 0.75, 1.0, and 1.25 g/l), initial RB concentration (10, 20, 30, and 40 mg/l), and the solution pH (3, 5, 7, 9, and 11) were studied.

Figure 1 | Designed photocatalytic batch reactor.

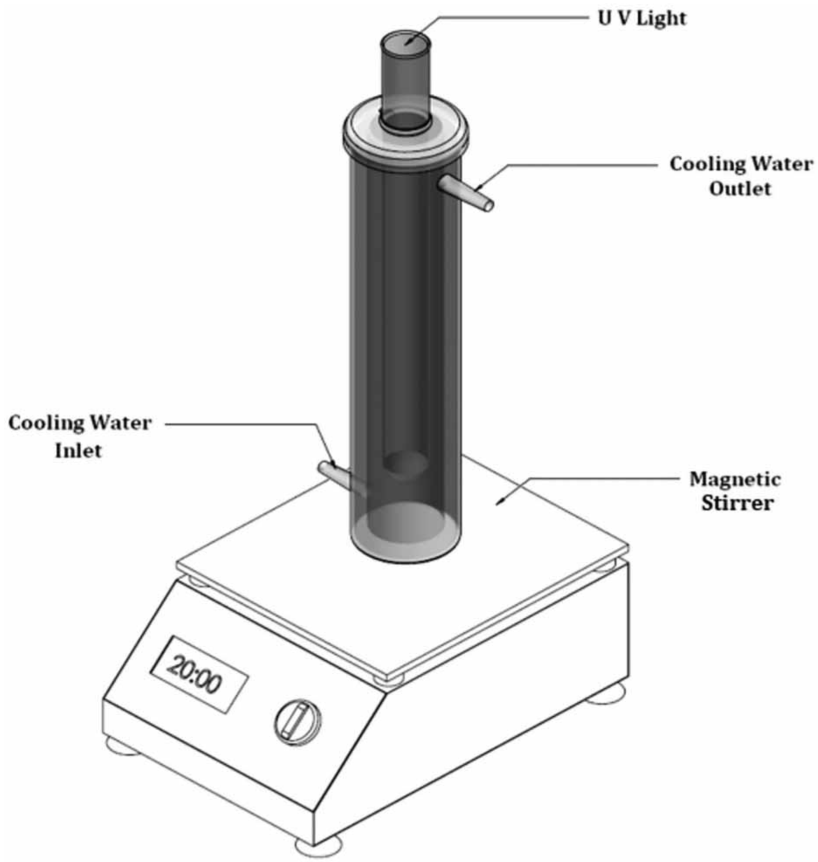


Figure 2 | Photocatalytic degradation experimental setup.

Impact of the catalyst dosage (Nb_2O_5)

Figure 3 illustrates how the amount of catalyst (Nb_2O_5) used affects the rate at which RB degrades. And it has been observed that slopes increase with the increasing catalyst (Nb_2O_5) dosage from 0.25 to 1.25 g/l for RB after that the degradation rate remains constant. In addition, an increase in the catalyst's (Nb_2O_5) dose was not seen to have any effect on the rate of RB's degradation. The destruction of photocatalytic degradation of RB has a dependence on the catalyst (Nb_2O_5) dosage, and as a result, there is a reduction in the photoactivated volume of suspension as a consequence of an increase in the turbidity of the solution brought about by a high catalyst (Nb_2O_5) dosage in conjunction with a reduction in the amount of UV light that is allowed to penetrate the substance. Therefore, the 1 g/l catalyst (Nb_2O_5) dose was fixed for RB, for further experimental studies.

Impact of RB initial concentration

The RB was subjected to photocatalytic degradation at a range of initial concentrations, which ranged from 10 to 40 mg/l. The effect of concentration (10–40 mg/l) of RB is shown in Figure 4 at the 1 g/l catalyst (Nb_2O_5) dose. It has been noticed, and the evidence can be seen in the figure, that as the concentration of RB increased, the rate of degradation decreased. The likely reason for this tendency is that the route length of the photons entering the solution gets shorter as the initial RB concentration gets higher, and the opposite impact can be seen in low concentrations. Therefore, an increase in the number of photons absorbed can be attributed to the catalyst in a lower concentration. So, for further experimental studies, the concentrations of RB 30 mg/l were fixed.

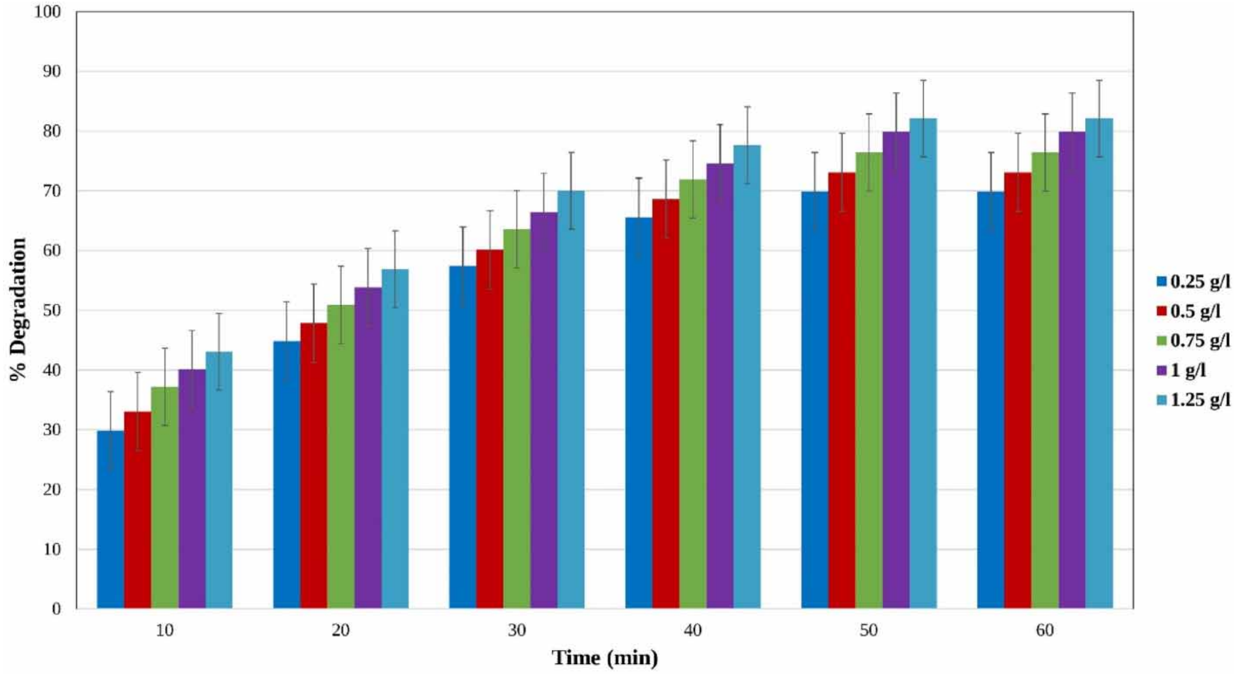


Figure 3 | Effect of the amount of catalyst (Nb_2O_5) on the rate of RB's degradation.

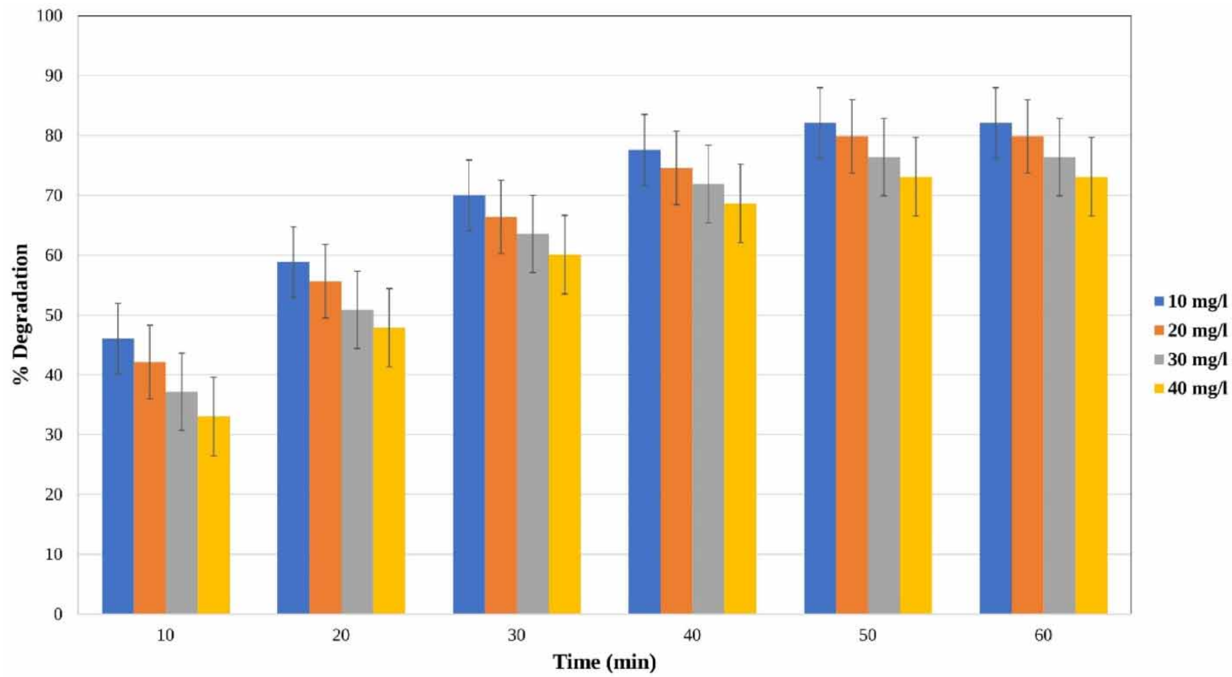


Figure 4 | Effect of initial concentration on RB degradation using a 1 g/l Nb_2O_5 catalyst.

Impact of pH

Solution pH is found to be a crucial factor in the photocatalytic degradation of dye. The effect of the pH study, experiments were conducted over a wide range of pH levels varies from 3 to 11 for steady 30 mg/l RB concentration and at the 1 g/l

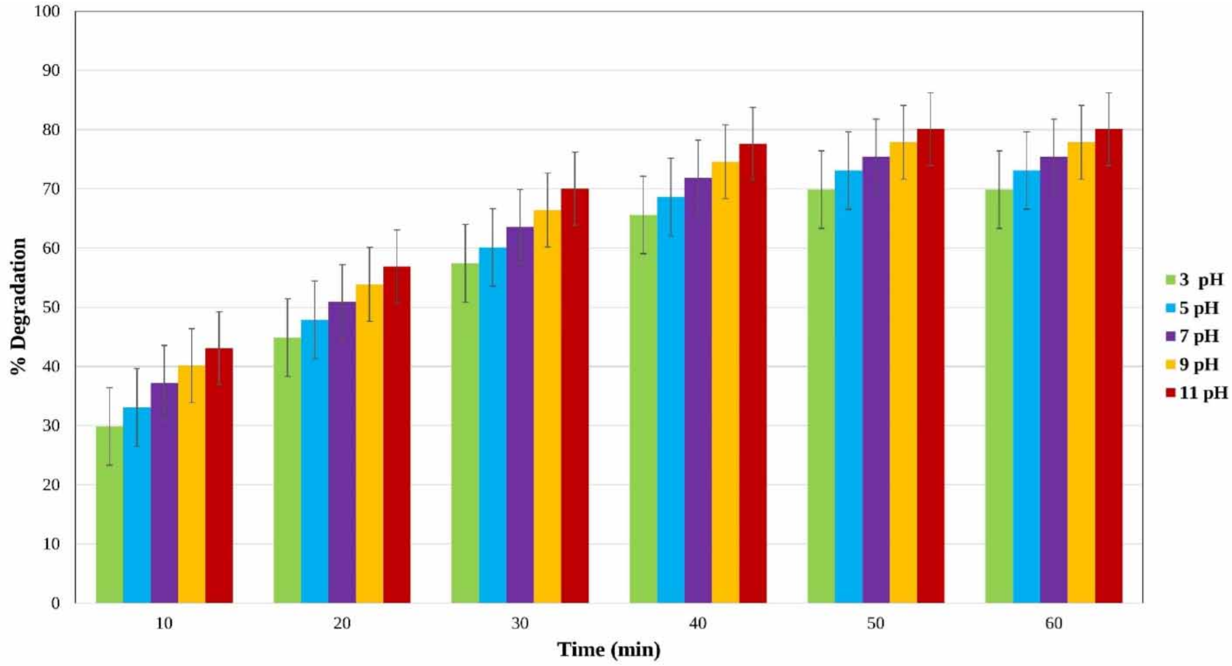


Figure 5 | Impact of pH on degradation of RB at 1 g/l catalyst (Nb_2O_5) dose and 30 mg/l RB concentration.

catalyst (Nb_2O_5) dose on the percentage degradation efficiency. The effect of pH on the degradation of RB at 1 g/l catalyst (Nb_2O_5) dose and 30 mg/l RB concentration is shown in Figure 5 and it has been observed with an increase in pH the percentage degradation initially increases and the observed maximum rate of degradation at pH 11 at 30 mg/l RB concentration and 1 g/l catalyst (Nb_2O_5) dose.

CONCLUSION

In the degradation of RB, the Nb_2O_5 was used as a catalyst. The degradation of RB is facilitated in the presence of a catalyst as experimental results confirmed. With an increase in catalyst dose up to an optimum loading, the initial rate of degradation of RB increased. Further, it showed no effect on the degradation of RB, as a result of an increase in the catalyst dose. As the rate of degradation of RB decreased, the initial RB concentration increased. It also shows that the maximum degradation of RB was observed at optimal conditions, i.e. RB initial concentration is 10 mg/l, catalyst (Nb_2O_5) dosage is 1 mg/l, and the pH is 11.

DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

CONFLICT OF INTEREST

The authors declare there is no conflict.

ACKNOWLEDGEMENTS

This research work was funded by Institutional Fund Projects under grant no. (IFPIP:1296-961-1443). The authors gratefully acknowledge the technical and financial support provided by the Ministry of Education and King Abdulaziz University, DSR, Jeddah, Saudi Arabia.

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First received 1 July 2022; accepted in revised form 4 December 2022. Available online 12 December 2022