

Oxidation of Aromatic Aldehydes Using Oxone

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Discussion of green chemistry principles and practical demonstrations of the accompanying benefits through implementation of pedagogically useful experiments in the general and organic chemistry curricula are becoming widespread (1); however, only very few chemistry departments in the country currently have green chemistry laboratory modules as independent courses or as accompanying laboratory portions of organic chemistry courses. The Department of Chemistry at the University of Oregon, under the leadership of James Hutchison and Kenneth Doxsee, has established a viable undergraduate green organic chemistry laboratory curriculum that offers a training ground for the undergraduate participants in all aspects of techniques and procedures that are part of a full-fledged second-year organic chemistry experience (2). The Department of Chemistry at the University of Scranton also offers its students an undergraduate laboratory experience in green chemistry (3). A major factor impeding the widespread introduction of green chemistry experiments in the organic chemistry laboratory curriculum is the unavailability of established experimental procedures and protocols that cover a wide array of concepts and reactions that are pedagogically relevant for second-year students. This article describes a convenient protocol for oxidation of aldehydes in water or a water–ethanol mixture using Oxone, a nontoxic and eco-friendly reagent.

Oxidation of alcohols to the corresponding carbonyl compounds and oxidation of aldehydes as synthetic routes for carboxylic acids or as a derivatization tool for the identification of “unknown” aldehydes during the qualitative analysis portion of the organic chemistry laboratory curriculum are common procedures in undergraduate laboratories. Use of household bleach (sodium hypochlorite, NaOCl) for the oxidation of alcohols in acetic acid is a well-known experiment highlighting the environmental and health benefits of using an innocuous reagent such as NaOCl (4) over more commonly known and used chromium-based reagents that pose both environmental and health risks (5). Oxidation of aldehydes to the corresponding carboxylic acids, on the other hand, are commonly carried out using KMnO_4 in acidic or basic media, or $\text{K}_2\text{Cr}_2\text{O}_7$ in acidic medium or chromic acid (6). These heavy metal-based reagents are hazardous and the protocols produce metal wastes that require special handling owing to their toxicities. Considering the pedagogical importance of oxidation of aldehydes in an undergraduate laboratory curriculum, it is desirable that greener approaches to the oxidation of aldehydes to carboxylic acids are developed.

Use of innocuous auxiliary reaction components, such as solvents, reagents, and separation agents, is one of the main principles of green chemistry (7). In this context, the use of water as a reaction medium provides many advantages, including its non-toxicity, non-flammability, low cost, and

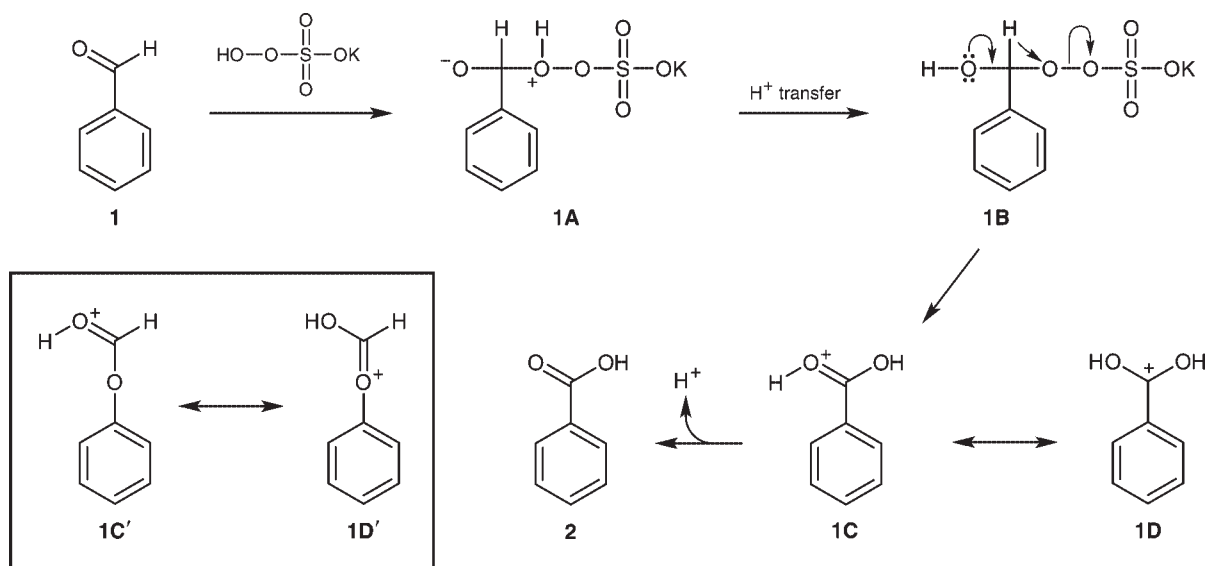
abundance (8). Precipitation and subsequent easy isolation by filtration of insoluble products is an added advantage of using water. Recently Borhan and co-workers described a convenient procedure for oxidation of aromatic aldehydes using Oxone in dimethylformamide (9). Oxone, commercially available from Aldrich Chemical Company, is a 2:1:1 molar mixture of KHSO_5 , KHSO_4 , and K_2SO_4 and is readily soluble in water. Considering the water-solubility and the environmentally safe and benign nature of Oxone, we recently used this reagent in conjunction with another oxidant for the oxidation of alcohols to carboxylic acids (10). Through this study we established that Oxone is incapable of oxidizing alcohols to aldehydes but readily oxidizes aldehydes to carboxylic acids. This observation prompted us to believe that a green experimental protocol for the oxidation of aromatic aldehydes using Oxone in water or a water–ethanol mixture could be developed and the isolation of the product should be feasible through simple filtration of the precipitated product obtained upon cooling the reaction mixture.

Mechanism

A plausible mechanism of oxidation of aldehydes using Oxone is reminiscent of Baeyer–Villiger oxidation and is, thus, instructive and conceptually comprehensible to an average second-year organic chemistry student (Scheme 1). Potassium persulfate (KHSO_5) present in Oxone is presumed to be the active oxidant that generates the peroxyacetal intermediate **1B** upon nucleophilic addition to the carbonyl carbon. The energetically favored scission of the weak O–O bond is accompanied by a hydride migration as shown to produce the oxonium ion intermediate **1C**, which subsequently loses a proton to give the final carboxylic acid product. The preferential migration of H over the phenyl group from **1B** can be justified if one considers the resonance stabilization of **1C** versus **1C'**, which would be the oxonium ion intermediate obtained upon phenyl migration. The benzylic stabilization available for **1D**, the less stable resonance contributor of **1C**, with an incomplete octet is not a viable stabilization feature for **1D'** as the involvement of π electrons will result in even less stable charge-separated resonance contributors with the negative charge on carbon, a non-electronegative atom. A discussion of the preferential migratory aptitude of H over phenyl group can be expected to be part of a detailed laboratory report or could be posed as a pre- or postlab question.

Green Chemistry Objectives

This experiment, a green oxidation of aromatic aldehydes to the corresponding carboxylic acids, was developed with



Scheme 1. Mechanism of oxidation of benzaldehyde to benzoic acid using Oxone.

an understanding that the following green objectives can be demonstrated to the students: (i) use of water as a viable solvent to conduct oxidation of aldehydes, (ii) use of a water-ethanol mixture as an alternate and eco-friendly solvent system for substrates that are completely insoluble in water, even at elevated temperatures, (iii) use of Oxone, an innocuous oxidizing agent that produces benign byproducts, and finally, (iv) easy isolation of the carboxylic acid product that precipitates upon cooling the reaction mixture and a resulting avoidance of extraction solvents in the product isolation procedure.

Experimental Overview

Oxidation of aldehydes using Oxone under both macro-scale and microscale reaction conditions has been achieved. Benzaldehyde, 1, and substituted benzaldehydes 3–7 (Figure 1) are oxidized to the corresponding carboxylic acids using this protocol. While the oxidation of benzaldehyde is conveniently carried out in water, the oxidation of the substituted benzaldehydes is carried out in a water-ethanol mixture (4:1 v/v). In all cases reported here, the carboxylic acid products are precipitated along with potassium salts from Oxone upon cooling the reaction mixture. Careful washing of the isolated solid with ice cold water effects selective dissolution of inorganic salts from the acid product. It is anticipated that incorporating this experiment in the organic chemistry laboratory curriculum would occur during the second term, by which time students are already trained in refluxing reactions, separating solids by vacuum filtration, and recrystallizing products. The experimental procedure was optimized so students could successfully carry out the experiment, isolate the product, and characterize the purified product through melting point determination and ¹H NMR spectroscopy during a three-hour laboratory period.

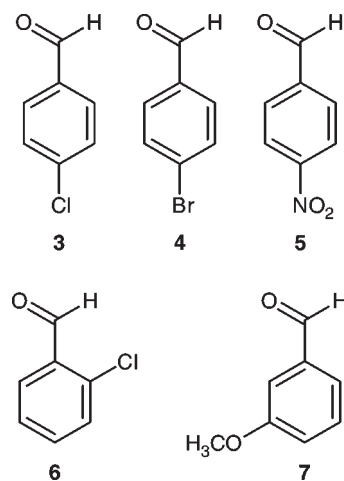


Figure 1. Structures of the substituted benzaldehydes.

Experimental Procedure

Benzaldehyde (1.0 g, 9.4 mmol), Oxone (FW = 614.8 g mol⁻¹, 7.25 g, 11.8 mmol),¹ and water (25 mL) were added to a 50-mL round-bottom flask fitted with a reflux condenser and a stir bar. The flask was then carefully lowered into a water bath maintained between 70–80 °C and left stirring at that temperature for 75 min, during which time the Oxone completely dissolved and the reaction mixture turned light brown. After the reflux period, without disassembling the reflux condenser, the flask was cooled in an ice bath for 15–20 min. The precipitated benzoic acid contaminated with potassium salts was filtered at the pump and washed well with ice cold water (20–30 mL). The crude product thus obtained was air dried and weighed. Average yield of the crude product ranged from 70–93%. Recrystallization of the crude prod-

uct from hot water gave pure benzoic acid, sharply melting at the expected temperature of 121–122 °C.

Oxidations of substituted benzaldehydes 3–7 are similarly carried out in a water–ethanol mixture (25 mL, 4:1 v/v) as the solvent. Average yields of the crude products varied from 65–90%, depending on the substrate and the extent and duration of the final cooling step prior to filtration of the product. ^1H NMR spectra of the crude products in all cases indicated purity of the isolated product to be greater than 90%, with the starting aldehyde being the only contaminant. Oxidation of the aldehydes using this protocol was also successfully carried out in microscale quantities and a typical procedure is included in the Supplemental Material.^W

Hazards

Aldehyde substrates employed in this experiment namely, benzaldehyde, 2-chlorobenzaldehyde, 4-chlorobenzaldehyde, 4-nitrobenzaldehyde, 4-bromobenzaldehyde, and *m*-anisaldehyde and the oxidizing agent, Oxone, are all irritants and thus necessary precautions should be taken when handling these chemicals. Though the experiment does not present any particular safety hazard, it is recommended that the students wear protective goggles, shoes, clothing and gloves at all times and carry out the procedures in a well vented fume-hood.

Conclusion

This experiment demonstrates the feasibility of using water as a solvent for organic reactions and highlights the cost and environmental benefits of its use. The use of relatively innocuous Oxone as the oxidizing agent and the formation of harmless potassium salts formed as byproducts also enhances the eco-friendly aspect of the procedure. The experiment also encourages students to think in terms of the reaction mechanism of the oxidation of aldehydes knowing that potassium persulfate is the active oxidant in Oxone. Recording of the ^1H NMR spectrum of the crude product allows students to calculate the extent of purity of the acid product through integration of the appropriate signals.

Acknowledgments

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^WSupplemental Material

A typical microscale procedure, notes to the instructor, instructions for the students including prelab and postlab exercises, and copies of ^1H NMR spectra of the crude products isolated are available in this issue of *JCE Online*.

Note

1. The number of moles of potassium persulfate (the active oxidant) present in the amount of Oxone used is 23.6 mmol, double the amount required for complete oxidation of the aldehyde. Experimentally it was convenient to use such an excess to ensure complete oxidation of the aldehyde thereby making the product isolation and purification easy.

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