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Nitrogen oxides and nitric acid enable the sustainable hydroxylation and nitrohydroxylation of benzenes under visible light irradiation

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Supporting Information Placeholder

ABSTRACT: A new type of waste recycling strategy is described in which nitrogen oxides or nitric acid are directly employed in photocatalyzed hydroxylations and nitrohydroxylations of benzenes. Through these transformations, otherwise costly denitrification can be combined with the synthesis of valuable compounds for various applications.

High levels of sustainability¹ can be achieved when waste products, which would otherwise require costly procedures for their disposal, can instead be utilized for the production of valuable chemical compounds or intermediates.² With regard to acute toxicity, nitrogen monoxide³ and dioxide⁴ are among the most dangerous waste gases, and industrial denitrification is currently achieved through two main strategies which are known as selective catalytic reduction (SCR)⁵ and selective non-catalytic reduction (SCNR).⁶ As these processes do however only lead to dinitrogen as final product, no value generation besides the denitrification itself is achieved. Alternatively, nitrogen oxides can be trapped in a wet scrubber containing aqueous hydrogen peroxide.7 Via absorption, if so, oxidation and disproportionation steps, this process leads to nitric acid as a low-value product.8 Other combinations of denitrification and synthesis, especially ones which could convert NO or NO2 into more valuable compounds, are however yet rare,⁹ and do thus represent a challenging field of research.

Against this background, our attention was drawn to the industrially important conversion of benzene to phenol.¹⁰ Over the last years, the search for enhancements of the traditional multi-step cumene process¹¹ has attracted much attention among chemists. The lately developed catalytic strategies turning benzene directly into phenol can thereby be grouped into catalytic oxidations using oxidants such as molecular oxygen,¹² hydrogen peroxide¹³ or dinitrogen oxide.^{14,15} Alternatively, phenol can be obtained through a variety of photocatalyzed reactions, in which mainly water acts as the source for the newly introduced hydroxy group.^{16,17} If such reaction could now be coupled to the use - or even better the consumption - of nitrogen oxides, or of nitric acid, a highly sustainable transformation would be realized. The envisioned process, which exploits the appealing photocatalyzed oxidation of benzene by DDQ,^{18,19} is depicted in Scheme 1. Photoactivated ³DDQ*, being formed under visible light irradiation via the short-lived singlet state

¹DDQ*, was expected to oxidize benzene (1) to its corresponding radical cation 2 by a single electron transfer (SET) process (A). Trapping of 2 by water, and rearomatization combined with electron, proton or hydrogen atom transfer steps, leads to phenol (3) and DDQH₂ (B).





Due to the necessary presence of water for the capture of radical cation **2**, and of dioxygen, if a nitrogen oxide containing waste gas was used, we assumed that nitric acid would have to be the actual oxidant for the regeneration of DDQ from DDQH₂ (**C**).^{20,21} This particular feature could then enable a novel type of difunctionalization of benzene,²²⁻²⁵ as the primarily formed phenol (**3**) might undergo nitration reactions to give nitrophenols **4** (**D**). Regarding the combination of denitrification and synthesis, the final nitration step is of importance as it could consume significant amounts of nitric acid, whereas the reoxidation cycle is likely to be catalytic in HNO₃.

Preliminary studies were conducted to evaluate the general feasibility of the nitrogen oxide-based hydroxylation on preparatively meaningful reaction scales. After first experiments with nitrogen monoxide on a 0.45 mmol scale, we further increased the scale by a factor of 12.5 (see Supporting Information). The hydroxylation reaction can then produce a maximum amount of 0.53 g of phenol (**3**) from 0.50 mL (5.6 mmol) of benzene (**1**). Variations on this scale included the reaction temperature (0-35°C), the amounts of DDQ (0.03-0.6 equiv) and nitrogen monoxide (0.05-0.2 equiv) as well as the light source, so that three variants **A-C** could finally be determined (Table 1, entry 1). The yields of 66% and 71%, in which phenol (**3**) was obtained under UV irradiation, correspond to turnover numbers of 4.4 and 4.7, respectively, relative to the photocatalyst DDQ. Irradiation by blue LED light gave the highest yield of 78% corresponding to a TON of 5.2. As the catalyst DDQ is not significantly consumed in the reaction course (see recovery experiments below), it appears plausible that the limited TON are due to the increasing light absorption of the reaction mixture and the growing amount of phenol, which both render the catalyst less efficient.

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 Table 1. Evaluation of NO and other oxidants in the photocatalyzed hydroxylation of benzene.

atalyzed nydroxylation of benzene.							
DDQ (0.15 equiv), oxidant (0.10 equiv), air hv (315-405 nm), rt (A) or hv (315-405 nm), 35 °C (B) or hv (450-475 nm), 30° C (C) $H_{3}CN/H_{2}O$ (65:1) 1 (5.6 mmol) 3							
		conditions ^a					
entry	oxidant(s)	A (UV) yield (%)	B (UV) yield (%)	C (Vis) yield (%)			
1	NO	66	71	78			
2	HNO_2^b	66	67	$76 (3/2)^d$			
3	HNO ₂ /HNO ₃ ^{b,c}	61	61	$78 (4/2)^d$			
4	HNO ₃	70	73	90 (2/1) ^d			
5	<i>t</i> BuONO	63	64	77 $(5/5)^d$			

^{*a*}General conditions: Benzene (5.6 mmol), DDQ (0.15 equiv), oxidant (0.10 equiv), CH₃CN/H₂O (113 mL:1.66 mL), closed air-filled reaction tube with pressure equilibration, iron UV lamp (250 W, 315-405 nm) or blue LED (8 W, 450-475 nm), 24 h. Yields after purification by column chromatography. ^{*b*}HNO₂ generated in situ from NaNO₂/HCl, ^{*c*}HNO₂ and HNO₃ each 0.05 equiv. ^{*d*}2-Nitrophenol and 4-nitrophenol obtained as side-products, respective yields given in brackets.

Having shown the feasibility of the phenol synthesis with NO under air as simulated waste gas, the conditions A-C were next applied in a study on alternative oxidants, which are closely related to NO and thus also to denitrification (Table 1, entries 2-4). The mixture of HNO₂ and HNO₃ reflects the products arising from the disproportionation of NO₂ in water,²⁰ and *tert*-butyl nitrite was included for comparison, as this oxidant was originally used in the DDQ-catalyzed hydroxylations of benzene (entry 5) by Fukuzumi.¹⁸ An inspection of all results summarized in Table 1 shows that highest yield in each column was achieved with HNO₃ (entry 4). Assuming that all other oxidants (entries 1-3, 5) finally also end up as HNO₃ under the given aerobic reaction conditions,²⁰ which is supported by the generally acidic pH value, it appears that the additional reaction steps converting the other oxidants to HNO₃ are not beneficial for the benzene hydroxylation itself. The initial presence of HNO₂ (entries 2 and 3) did not turn out as favorable, although HNO_2 has been reported to be a more efficient oxidant than HNO₃.²⁶ Interestingly, the reaction with NO under the energetically more attractive LED irradiation (entry 1, conditions C) was the only experiment providing phenol (3) without contamination by 2or 4-nitrophenol.

To investigate the broader applicability of the nitrogen monoxide based benzene hydroxylation, the more successful conditions **B** and **C** were next used to convert fluoro-, chloro- and bromobenzene **1a-c**. Since the hydroxylation using HNO₃ under visible light irradiation (blue LED) had given a high yield of 90%, these conditions were also included. In contrast to the hydroxylation of benzene (**1**), which was most successful under conditions **C** using HNO₃ (entry 1), the reactions with the halobenzenes **1a-c** gave the highest yields when NO was used under visible LED light irradiation (entries 2-4). Again, no side-products from nitration were observed in reactions using NO, whereas HNO₃ furnished such by-products in yields of 3-8%. The *ipso* substitution of fluorobenzene (**1a**) to give phenol (**3**), which is a particular side-reaction of **1a**,¹⁸ preferably occurred under visible light, as up to 25% of **3** were formed under conditions **C** compared to 6% under conditions **B** using UV light.

 Table 2. Hydroxylation of benzene and halogenated benzenes.

$\begin{array}{c} \text{DDQ } (0.15 \text{ equiv}), \text{air} \\ \text{NO, } \text{hv } (UV), 35 ^{\circ}\text{C } (\textbf{B}) \\ \text{or NO, } \text{hv } (Vis), 30^{\circ}\text{C } (\textbf{C}) \\ \textbf{Or HNO_3, } \text{hv } (Vis), 30^{\circ}\text{C } (\textbf{C}) \\ \textbf{Or HNO_3, } \text{hv } (Vis), 30^{\circ}\text{C } (\textbf{C}) \\ \textbf{CH_3CN/H_2O } (65:1) \\ \textbf{1,1a-c } (5.6 \text{ mmol}) \\ \end{array}$						
	conditions ^a					
		B (UV)	C (Vis)	C (Vis)		
		NO	NO	HNO ₃		
	phenol	yield ^b	yield ^b	yield ^b		
entry	3 : R =	(%)	(%)	(%)		
1	3 : H	71	78	90 ^g		
2	3a : F	51 [8:43] ^d	64 [13:51] ^e	48 [10:38] ^{f,g}		
3	3b : Cl	65 [13:52]	78 [15:63]	73 [13:60] ^g		
4	3c : Br	36 [5:31]	54 [10:44]	45 [6:39] ^g		

^{*a*}General conditions: see below Table 1. ^{*b*}Yields after purification by column chromatography. Yields of 2- and 4-substitution products given in brackets. ^{*d*}Along with 6% of phenol (**3**). ^{*e*}Along with 25% of phenol (**3**). ^{*f*}Along with 20% of phenol (**3**). ^{*g*}Along with nitrophenols (3-8%).

Encouraged by the observation of small amounts of nitrohydroxylation products in reactions with HNO_3 , we next examined the feasibility of the double functionalization (Scheme 2).





^aYields based on DDQ. Yields determined by ¹H-NMR using dimethyl terephthalate as internal standard.

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For that purpose, two-phase mixtures of benzene and nitric acid containing DDQ were irradiated with UV or visible light. Already at the initial concentration of 0.72 M HNO₃ it became apparent that hydroxylation and mononitration, leading to nitrophenols 5a and 5b, cannot be achieved selectively and with high yield under these conditions. We therefore focused on the dinitrophenols **6a** and **6b**, which were obtained in maximum yields of 54% and 249% under UV irradiation from 9.3 M HNO₃ and in maximum yields of 62% and 233% under visible light irradiation from 7.2 M HNO₃. A comparison of the product distributions reveals that visible light irradiation can produce 6a and 6b from benzene more effectively at lower concentrations, especially from 1.8 and 3.6 M HNO₃. On the other hand, the competing formation of nitrobenzene (7) becomes more distinct under visible light irradiation at practically all concentrations of HNO₃ higher than 1.8 M.

In this context, it was interesting to observe that some of the nitration steps leading to products 5-7 are light-dependent (Scheme 3).²⁷ In control reactions with 3.6 M HNO₃ and DDQ in the absence of light, no conversion of benzene (1) took place under otherwise identical conditions, thereby showing that the conversion to **3** as well as the "background nitration" to **7** are light-induced (Scheme 3).

Scheme 3. Control reactions in the absence of irradiation.^a



^{*a*}Reaction conditions: **1** (3.0 mL) or **3**, **5a** or **5b** (0.15 mmol), DDQ (0.15 mmol), HNO₃ (3.6 M, 1.5 mL), air-filled, closed reaction tube with pressure equilibration, 30 °C, 24 h.

Furthermore, 2-nitrophenol (**5a**), which is the necessary precursor of **6a**, and possibly of **6b**, remained fully stable in the absence of light, so that irradiation also appears to be required for the formation of **6a**. This was confirmed by the experiment with phenol (**3**), which gave **5a**, **5b** and **6b**, but not **6a** in the dark. 4-Nitrophenol (**5b**) was, as expected, readily nitrated to give **6b** in the absence of light. This study points to the interesting aspect that nitration reactions could be influenced by irradiation. However, it can currently not be excluded that compounds that are formed as intermediate products also exert catalytic effects which in turn influence product formation and distribution.

Finally, the optimized conditions (Scheme 2) were applied to benzene (1) and halobenzenes **1a-c** on a larger, 10-fold reaction scale (Scheme 4). Under these conditions, 2,6-dinitrophenol (**6a**) and 2,4-dinitrophenol (**6b**) were formed in slightly lower yields of 50% and 200%, respectively, than on smaller scale (Scheme 2), whereat more than 85% of the photocatalyst DDQ could be recovered. Additional experiments, in which the nitric acid solution from a previous nitrohydroxylation reaction was reused after extraction of **6a** and **6b** and DDQ by dichloromethane, gave the desired products **6a** and **6b** again in acceptable yields (see 2nd and 3rd run, Scheme 3). When starting from the halobenzenes **1a-c**, the best results were obtained for chlorobenzene (**1b**), followed by **1a** and **1c**, which is in agreement with the order observed in the hydroxylation reactions (Table 2). Scheme 4. Nitrohydroxylation of benzene and halobenzenes.^a



^{*a*} Reaction conditions: **1,1a-c** (30 mL), DDQ (1.5 mmol), HNO₃ conc. (10 mL), H₂O (10 mL), air-filled, closed reaction tube with pressure equilibration, LED (8 W, 450-475 nm), 30 °C, 24 h. Yields determined by ¹H-NMR using dimethyl terephthalate as internal standard. Yields based on DDQ.

In summary, it has been shown that the photocatalyzed hydroxylation of benzene can be coupled to the use of NO or HNO₃, which closely links this industrially important transformation to the environmentally significant topic of denitrification. While the use of NO was found to lead to pure phenols, without contamination by nitro compounds, HNO₃ allowed for higher yields and enabled a so far unknown type of double functionalization. The dinitrophenols, which are now directly accessible from benzene through a highly sustainable process, are known as valuable intermediates for the production of explosives, dyes, wood preservers, herbicides and photographic developers as well as for many other applications.²⁸

EXPERIMENTAL SECTION

General experimental. Solvents and reagents were obtained from commercial sources and were used as received. NMR spectra were recorded on Bruker Avance 600 (1H: 600 MHz, 13C: 151 MHz) and Bruker Avance 400 (1H: 400 MHz, 13C: 101 MHz). For 1H NMR CDCl₃ or DMSO-d₆ was used as solvent referenced to TMS (0.00 ppm), CDCl₃ (7.26 ppm) or DSMO-*d*₆ (2.50 ppm). For ¹³C NMR DMSO-d₆ was used as solvent referenced to DMSO-d₆ (39.52 ppm). Chemical shifts are reported in parts per million (ppm). Coupling constants are in Hertz (J Hz). The following abbreviations are used for the description of signals: s (singlet), d (doublet), t (triplet), q (quartet), m (multiplet) and bs (broad singlet). Electrospray-ionization MS (ESI-MS) measurements were performed on a UHR-TOF Bruker Daltonik (Bremen, Germany) maXis plus, an ESIquadrupole time-of-flight (qToF) mass spectrometer capable of resolution of at least 60.000 FWHM. Detection was in negative ion mode, the source voltage was 2.8 kV. The flow rates were 180 µL/hour. The drying gas (N₂), to aid solvent removal, was held at 180 °C and the spray gas was held at 20 °C. The machine was calibrated prior to every experiment via direct infusion of the Agilent ESI-TOF low concentration tuning mixture, which provided an m/z range of singly charged peaks up to 2700 Da in both ion modes. Analytical TLC was carried out on silica gel plates using short wave (254 nm) UV light and CAM [1.0 g Ce(SO₄)₂, 29 g ammonium molybdate, 25 mL H₂SO₄ in 200 mL H₂O] to visualize components. Silica gel (Kieselgel 60, grain size 40-63 µm) was used for column chromatography. For photocatalyzed reactions a 250W iron UV-lamp (black glass filter, transmission range: 315-405 nm) or an 8W blue LED lamp (emission range: 450-475 nm) was used.

General Procedure for the hydroxylation of benzene (Table 1). In a closed, air-filled reaction tube with pressure equilibration benzene (1) (5.6 mmol, 0.5 mL), DDQ (0.84 mmol, 192 mg, 0.15 eq), water (1.66 mL) and the oxidant (0.56 mmol, 0.10 eq) were dissolved in CH₃CN (113 mL). In case of nitrogen monoxide, NO (0.56 mmol, 12.5 mL) was injected into the gas phase of the reaction vessel. In the case of nitrous acid, sodium nitrite (0.56 mmol, 38.6mg) and 1N hydrochloric acid (0.56 mmol, 560µL) were added to the solution. For the combination of nitrous and nitric acid, sodium nitrite (0.28 mmol, 19.3 mg), 1N hydrochloric acid (0.28 mmol, 280µL) and nitric acid (0.28 mmol, 17 µL, 14.35M) were added to the reaction mixture. Nitric acid (0.56 mmol, 33.9 µL, 14.35M) was added to the solution directly. TBN (0.56 mmol, 66.6 µL) was also added directly to the reaction mixture.

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The resulting solution was irradiated either with a 250W UV lamp (conditions **A** and **B**) or a 8W LED lamp (condition **C**) under vigorous stirring for 24 h. Afterwards the mixture was extracted with CH₂Cl₂ (3×150 mL) and the combined organic phases were dried over sodium sulfate. The solvent was concentrated slowly under reduced pressure (to 200 mbar) and the crude product was purified by column chromatography (hexane/ethyl acetate = 6:1).

Phenol (3): 477 mg, 5.1 mmol, 90 % using HNO₃ and LED (c.f. entry 4); ¹H NMR (400 MHz, CDCl₃): δ (ppm) = 6.84 (dd, J = 1.0 Hz, J = 8.6 Hz, 2 H), 6.91 (t, J = 7.4 Hz, 1 H), 7.23 (dd, J = 7.4 Hz, J = 8.6 Hz, 2 H). The analytical data obtained is in agreement with those reported in literature.²⁹

General Procedure for the hydroxylation of halobenzenes 1a-c (Table 2). In a closed, air-filled reaction tube with pressure equilibration, benzene (1) or the halogenated benzene derivative 1a-c (5.6 mmol), DDQ (0.84 mmol, 192 mg, 0.15 eq), water (1.66 mL) and the oxidant nitric acid (0.56 mmol, 33.9 μ L, 14.35M) were dissolved in CH₃CN (113 mL). In the case of nitrogen monoxide, nitric acid was replaced by NO (0.56 mmol, 12.5 mL), which was added to the gas phase. The resulting solution was irradiated either with a 250W UV lamp or an 8W LED lamp under vigorous stirring for 24 h. Afterwards the mixture was extracted with CH₂Cl₂ (3 × 150 mL) and the combined organic phases were dried over sodium sulfate. The solvent was concentrated slowly under reduced pressure (to 200 mbar) and the crude product was purified by column chromatography (hexane/ethyl acetate = 8:1 to 6:1 to 4:1 to 2:1).

36 4-Fluorophenol (**3a**): 325 mg, 2.9 mmol, 51 % using NO and LED 37 (c.f. entry 2); ¹H NMR (600 MHz, CDCl₃): δ (ppm) = 6.77 (ddd, 38 J = 2.7 Hz, J = 4.9 Hz, J = 6.7 Hz, 2 H), 6.92-6.86 (m, 2 H). The 39 analytical data obtained is in agreement with those reported in lit-40 erature.³⁰

41 2-Fluorophenol (**3a**'): 76 mg, 0.73 mmol, 13 % using NO and LED (c.f. entry 2); ¹H NMR (600 MHz, CDCl₃): δ (ppm) = 6.86-6.80 (m, 1 H), 7.09-6.94 (m, 3 H). The analytical data obtained is in agreement with those reported in literature.³¹

44 4-Chlorophenol (**3b**): 454 mg, 3.5 mmol, 63 % using NO and LED 45 (c.f. entry 3); ¹H NMR (600 MHz, CDCl₃): δ (ppm) = 6.79 (d, 46 J = 8.9 Hz, 2 H), 7.17 (d, J = 8.9 Hz, 2 H). The analytical data ob-47 tained is in agreement with those reported in literature.³⁰

2-Chlorophenol (**3b**'): 108 mg, 0.84 mmol, 15 % using NO and LED (c.f. entry 3); ¹H NMR (600 MHz, CDCl₃): δ (ppm) = 6.88-6.82 (m, 1 H), 7.01 (dd, J = 1.6 Hz, J = 8.2 Hz, 1 H), 7.28-7.22 (m, 1 H), 7.31 (dd, J = 1.6 Hz, J = 8.2 Hz, 1 H). The analytical data obtained is in agreement with those reported in literature.³²

52 4-Bromophenol (**3c**): 426 mg, 2.5 mmol, 44 % using NO and LED 53 (c.f. entry 4); ¹H NMR (400 MHz, CDCl₃): δ (ppm) = 6.72 (d, 54 J = 8.9 Hz, 2 H), 7.28 (d, J = 8.9 Hz, 2 H). The analytical data obtained is in agreement with those reported in literature.³⁰ 2. Person product and the second second terms of the second terms of terms of

2-Bromophenol (**3c'**): 97 mg, 0.56 mmol, 10 % using NO and LED (c.f. entry 4); ¹H NMR (400 MHz, CDCl₃): δ (ppm) = 6.79 (ddd, *J* = 1.5 Hz, *J* = 7.4 Hz, *J* = 8.0 Hz, 1 H), 6.98 (dd, *J* = 1.5 Hz, 58 J = 8.0 Hz, 1 H), 7.25 (dd, J = 7.4 Hz, J = 7.4 Hz, 1 H), 7.46 (dd, J = 1.5 Hz, J = 8.0 Hz, 1 H). The analytical data obtained is in agreement with those reported in literature.³³

General Procedure for the nitrohydroxylation of benzene (Scheme 2). Benzene (1) (3 mL), DDQ (0.15 mmol, 34.1 mg) and nitric acid (2 mL, for concentrations, see Scheme 2) were added to a closed air-filled reaction tube with pressure equilibration. The resulting biphasic mixture was irradiated either with a 250W UV-lamp or an 8W LED-lamp for 24 h under vigorous stirring. Afterwards the mixture was extracted with CH₂Cl₂ (3×30 mL) and the combined organic phases were dried over sodium sulfate. The solvent was concentrated slowly under reduced pressure (to 10 mbar) and the crude product was obtained as a yellow-orange liquid. Analysis of the product distribution was performed by ¹H NMR spectroscopy in CDCl₃ using dimethyl terephthalate as internal standard.

2-Nitrophenol (**5a**): ¹H NMR (600 MHz, CDCl₃): δ (ppm) = 7.0 (ddd, J = 1.3 Hz, J = 7.2 Hz, J = 8.6 Hz, 1 H), 7.17 (dd, J = 1.3 Hz, J = 8.4 Hz, 1 H), 7.59 (ddd, J = 1.6 Hz, J = 7.2 Hz, J = 8.6 Hz, 1 H), 8.12 (dd, J = 1.6 Hz, J = 8.6 Hz, 1 H), 10.6 (s, 1 H). The analytical data obtained is in agreement with those reported in literature.³⁴

4-Nitrophenol (**5b**): ¹H NMR (400 MHz, CDCl₃): δ (ppm) = 6.91 (d, J = 9.2 Hz, 2 H), 8.18 (d, J = 9.2 Hz, 2 H). The analytical data obtained is in agreement with those reported in literature.³⁴

2,6-Dinitrophenol (**6a**): ¹H NMR (600 MHz, CDCl₃): δ (ppm) = 7.15 (t, *J* = 8.3 Hz, 1 H), 8.34 (d, *J* = 8.3 Hz, 2 H), 11.48 (s, 1 H). The analytical data obtained is in agreement with those reported in literature.³⁵

2,4-Dinitrophenol (**6b**): ¹H NMR (600 MHz, CDCl₃): δ (ppm) = 7.34 (d, J = 9.2 Hz, 1 H), 8.46 (dd, J = 2.7 Hz, J = 9.2 Hz, 1 H), 9.08 (d, J = 2.7 Hz, 1 H), 11.02 (s, 1 H). The analytical data obtained is in agreement with those reported in literature.³⁶

Nitrobenzene (7): ¹H NMR (600 MHz, CDCl₃): δ (ppm) = 7.55 (dd, J = 7.5 Hz, J = 8.6 Hz, 2 H), 7.70 (t, J = 7.5 Hz, 1 H), 8.24 (dd, J = 1.0 Hz, J = 8.6 Hz, 2 H). The analytical data obtained is in agreement with those reported in literature.³⁴

General Procedure for the nitrohydroxylation of benzene (1) and halobenzenes 1a-c (Scheme 3). In a closed air-filled reaction tube with pressure equilibration benzene (1) or the halogenated derivative 1a-c (30 mL), DDQ (1.50 mmol, 340.5 mg) and nitric acid (7.2 M, 20 mL) were combined to form the biphasic reaction mixture. The mixture was irradiated with an 8W LED-lamp for 24 h under vigorous stirring. Afterwards, the mixture was extracted with CH₂Cl₂ (3×150 mL) and the combined organic phases were dried over sodium sulfate. The solvent was concentrated slowly under reduced pressure (to 10 mbar) and the crude product was obtained as a yellow-orange liquid. Analysis of the product distribution was performed by ¹H NMR spectroscopy in CDCl₃ using dimethyl terephthalate as internal standard.

4-Fluoro-2,6-dinitrophenol (**7a**): ¹H NMR (400 MHz, CDCl₃): δ (ppm) = 8.11 (d, *J* = 7.1 Hz, 2 H), 11.2 (s, 1 H). The analytical data obtained is in agreement with those reported in literature.^{28e}

2-Fluoro-4,6-dinitrophenol (**7b**): ¹H NMR (400 MHz, CDCl₃): δ (ppm) = 8.31 (d, J = 2.7 Hz, J = 9.7 Hz, 1 H), 8.91 (d, J = 2.0 Hz, J = 2.7 Hz, 1 H), 10.96 (s, 1 H). The analytical data obtained is in agreement with those reported in literature.³⁷

4-Chloro-2,6-dinitrophenol (8a): ¹H NMR (400 MHz, CDCl₃): δ (ppm) = 8.32 (s, 2 H), 11.3 (s, 1 H). The analytical data obtained is in agreement with those reported in literature.^{28f}

2-Chloro-4,6-dinitrophenol (**8b**): ¹H NMR (400 MHz, DMSO-d₆): δ (ppm) = 8.23 (d, *J* = 3.1 Hz, 1 H), 8.59 (d, *J* = 3.1 Hz, 1 H). The analytical data obtained is in agreement with those reported in literature.³⁸

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4-Bromo-2,6-dinitrophenol (**9a**): ¹H NMR (400 MHz, CDCl₃): δ (ppm) = 8.44 (s, 2 H), 11.3 (s, 1 H). ¹³C NMR (151 MHz, DMSO-d₆): δ (ppm) = 124.2 (C_q), 125.2 (2×CH), 141.9 (C_q), 160.9 (C_q). HRMS (ESI): calcd. for C₆H₂O₅N₂⁷⁹Br [M⁻]: 260.9153, found: 260.9154. The analytical data is in agreement with those of an authentic sample prepared according to the general procedure for authentic samples (see below).

13 General Procedure for the preparation of authentic samples for the nitrohydroxylation of bromobenzene (1c): In a 50 mL flask 14 2-bromophenol (0.5 mmol, 57.9 µL) or 4-bromophenol (0.5 mmol, 15 59 mg) was dissolved in ethanol (1 mL) and H₂SO₄ (2 mL, 18M). 16 HNO₃ (1 mL, 14.4M) was added. The resulting solution was stirred 17 for 4 hours at room temperature. Afterwards the mixture was ex-18 tracted with ethyl acetate (3×5 mL), the combined organic phases 19 were dried over Na₂SO₄ and the solvent was removed under re-20 duced pressure.

Experiments under re-use of HNO₃ (Scheme 3): In a closed airfilled reaction tube with pressure equilibration benzene (1) (30 mL), DDQ (1.50 mmol, 341 mg) and nitric acid (7.2 M, 20 mL) were combined to form the biphasic reaction mixture. The mixture was irradiated with an 8W LED lamp for 24 h under vigorous stirring. Afterwards, the aqueous phase was separated from the organic layer and used for the same reaction again. This step was repeated twice. The organic layer was diluted with H₂O (100 mL), extracted with CH₂Cl₂ (3×150 mL) and dried over sodium sulfate. The solvent was concentrated slowly under reduced pressure (to 10 mbar) and the crude product was obtained as a yellow-orange liquid. Analysis of the product distribution was performed by ¹H NMR spectroscopy in CDCl₃ using dimethyl terephthalate as internal standard.

ASSOCIATED CONTENT

Supporting Information

Optimization experiments, control experiments, NMR spectra and pictures of experimental setup. The Supporting Information is available free of charge on the ACS Publications website.

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Notes

The authors declare no competing financial interests.

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