Unveiling the multiphase fate of 2,4-dinitrophenol on aerosols: Interfacial hydration modulates competing oxidation pathways and predicted toxicity indicatorsincrease in toxicity

Chenlei Wang[1], Ran Li[1], Jiaxing Sun[2], Zihan Zhang[1], Nan Zhao[1], Leilei Liu*[1], Zuju Ma[1], Maoxia He[3], Jianfei Sun*[1]

[1]School of Environmental and Material Engineering, Yantai University, Yantai 264005, P. R. China

[2]Shandong Pengbo Safety & Environmental Services Limited, Yantai 265600, P. R. China

[3]Environment Research Institute, Shandong University, Qingdao 266237, P. R. China

Keywords: Phenols; Multi-oxidant; Solvation effect; Density functional theory; Bio-toxicity

*Corresponding author. E-mail: Jianfei Sun: jianfeisun@ytu.edu.cn

Leilei Liu: liuleileimail@163.com

Abstract

This study elucidates the ~~atmospheric transformation~~ mechanisms of selected transformation pathways of 2,4-dinitrophenol (2,4-DNP) using an integrated computational framework. In the gas phase, the calculated initial reactions with~~oxidation by~~ hydroxyl radicals (•OH) and ozone (O_3) are kinetically more favorable than~~is identified as the dominant pathway, whereas~~ the direct reaction with nitrogen dioxide radical ($•NO_2$), which is kinetically hindered. In the aqueous phase, solvation –substantially modifies the calculated reaction kinetics~~effects suppress the reaction rates~~, ~~while~~ and the cumulative electron-withdrawing effect of the two nitro substituents lowers the O_3 reaction rate coefficient by ~~exert a cumulative electron-withdrawing effect that reduces the rate constant by three orders of magnitude relative to mononitrocatechol. This study elucidates selected transformation mechanisms of 2,4-dinitrophenol (2,4-DNP) using an integrated computational framework. In the gas phase, the calculated initial reactions with hydroxyl radicals (•OH) and ozone (O_3) are kinetically more favorable than the direct reaction with nitrogen dioxide radical ($•NO_2$), which is kinetically hindered. In the aqueous phase, solvation substantially modifies the calculated reaction kinetics, while the two nitro substituents exert a cumulative electron-withdrawing effect, resulting in a calculated O_3 reaction rate coefficient~~ approximately three orders of magnitude relative to~~lower than that of~~ mononitrocatechol. ~~For the key radical intermediate generated by •OH addition, hydrogen atom abstraction (HAA) by O_2 is kinetically favored over the investigated $•NO_2$ pathway based on the calculated barriers and an illustrative effective-rate comparison using representative atmospheric concentrations. At the gas-~~

~~aqueous interface, molecular dynamics (MD) simulations show a non-monotonic dependence of 2,4-DNP adsorption on hydration in the idealized C_{60}/water system, with adsorption strengthening at moderate hydration and weakening at high hydration. Finally, QSAR calculations predict that certain ozonolysis products exhibit higher Ames mutagenicity and developmental toxicity indicators than the parent compound, indicating product-specific changes in predicted toxicity profiles during oxidation. These screening-level predictions require experimental validation. Overall, these findings provide molecular-level mechanistic insights into selected transformation pathways and interfacial interactions of 2,4-DNP and motivate further experimental investigation of its transformation products and their toxicity.~~

~~–~~For the key radical intermediate generated by •OH addition, hydrogen atom abstraction (HAA) ~~with~~ by O_2 is kinetically favored over the competing $•NO_2$ pathway ~~represents the dominant atmospheric fate~~ based on the calculated barriers and an illustrative comparison of effective rates under representative atmospheric concentrations~~the overwhelming concentration advantage of O_2 over $•NO_2$~~. ~~–~~At the gas-aqueous interface, molecular dynamics (MD) simulations ~~demonstrate that the adsorption of 2,4-DNP onto the C60 aerosol surrogate is non-monotonically modulated by interfacial hydration—first strengthening at moderate hydration and weakening at high hydration.~~ show a non-monotonic dependence of 2,4-DNP adsorption on hydration in the idealized C60/water system, with adsorption strengthening at moderate hydration and weakening at high hydration. Finally, QSAR calculations predict that certain ozonolysis products exhibit higher predicted Ames mutagenicity and developmental toxicity indicators than

the parent compound, indicating product-specific changes in predicted toxicity profiles during oxidation. These screening-level predictions require experimental validation. ~~Finally, computational toxicology predicts that certain ozonolysis products exhibit elevated Ames mutagenicity and developmental toxicity indicators relative to the parent compound, suggesting that oxidative processing of 2,4-DNP may not lead to simple detoxification.~~ These findings provide ~~mechanistic insights into~~ molecular-level mechanistic insights into selected transformation pathways and interfacial interactions involving 2,4-DNP and motivate further experimental investigation of its transformation products and their toxicological properties. ~~the atmospheric transformation pathways of this specific dinitrophenol and highlight the importance of evaluating transformation product toxicity in the environmental risk assessment of nitrophenolic compounds.~~

1 Introduction

The complex physicochemical processes of atmospheric aerosols are central to understanding their roles in climate and environmental quality ~~Atmospheric aerosols, as pivotal regulators of the Earth's climate system and environmental quality, have long placed the complex study of their physicochemical processes at the forefront of scientific inquiry~~(Perumpully and Gautam, 2025; Mcneill, 2017). Among them, secondary organic aerosols (SOAs) exert substantial influences on the global radiation balance and public health (Li et al., 2022a; Kroll and Seinfeld, 2008). Their formation originates from the oxidation, nitration, and subsequent reactions of volatile organic compounds (VOCs), which generate semi-volatile and low-volatility products (Fan et al., 2022; Li et al., 2021; Mahilang et al., 2021). Within the diverse range of precursors, nitrophenolic compounds (NPs) are important toxic organic pollutants, primarily emitted from incomplete combustion of fossil fuels and biomass, and also formed via photochemical oxidation of precursors such as polycyclic aromatic hydrocarbons (Li et al., 2022b; Li et al., 2020; Salvador et al., 2021). Among them, 2,4-dinitrophenol (2,4-DNP) is listed as a priority pollutant by the U.S. Environmental Protection Agency due to its acute and chronic toxicity, potential genotoxicity, and bioaccumulation (Shukla et al., 2009; Yan et al., 2021). Although ambient concentrations of 2,4-DNP are typically in the ng m^{-3} range, its low volatility and favorable aqueous partitioning promote its presence in condensed phases such as aerosol water and cloud/fog droplets ~~high Henry's law constant and low vapour pressure lead to significant partitioning into condensed phases~~

such as aerosol particles and cloud/fog droplets(Lüttke and Levsen, 1997). Consequently, it can be deposited onto terrestrial and aquatic ecosystems via dry and wet deposition, posing sustained threats to the environment and human health. A molecular-levelcomprehensive understanding of its multiphase chemical transformation mechanisms is therefore essential for accurate risk assessment and fate prediction.improving mechanistic descriptions of its environmental transformation and for informing future fate and risk assessments.

Over the past two decades, extensive research has addressed the atmospheric chemistry of nitrophenols, yet the progress has been uneven across different phases. In the gas phase, kinetic measurements have established rate constants for the •OH initiated oxidation of nitrophenols (Bejan et al., 2007), while photolysis and •NO_3 mediated pathways are recognized as important loss processes, particularly at night (Bejan et al., 2007; Ng et al., 2017). In the aqueous phase, reactions with •OH radicals have been systematically quantified; for 2,4-DNP, the second order rate constants are $(1.76 \pm 0.05) \times 10^9$ M^{-1} s^{-1} for the neutral form and $(2.33 \pm 0.11) \times 10^9$ M^{-1} s^{-1} for the phenolate (Albinet et al., 2010), with similar kinetic data available for nitrocatechol, nitroguaiacol, and other dinitrophenols (Hems and Abbatt, 2018). However, these studies have mainly focused on homogeneous reactions, leaving the gas-liquid and gas-solid interfaces—key regions where reactivity often differs from the bulk phases—far less understood. Recent work has shown that oxidation of phenolic compounds at interfaces yields products distinct from those formed in the bulk (Pillar-Little et al., 2014; Pillar-Little and Guzman, 2017; Rana and Guzman, 2020; Rana and Guzman, 2022b,

a), underscoring the importance of elucidating the molecular level interactions that govern interfacial adsorption and reactivity. Nevertheless, the behavior of nitrophenols on carbonaceous aerosol surfaces remains largely unexplored.

This knowledge gap stems primarily from the extreme complexity of real carbonaceous particles, such as black carbon and soot. These particles, products of incomplete combustion, exhibit physicochemical properties that depend strongly on pyrolysis temperature, formation conditions, and subsequent atmospheric aging (Andreae and Gelencsér, 2006). Although their polyaromatic (graphite-like) surfaces can form π-π electron donor-acceptor complexes with nitroaromatic compounds, adsorption strength is significantly influenced by steric effects due to micropore filling and by fouling with natural organic matter that blocks pores and competes for sites (Cornelissen et al., 2005; Poster et al., 2007). Moreover, chemical heterogeneity (oxygen containing functional groups, defect sites, metal impurities) and morphological complexity (aggregates, pore structures) make it extremely difficult to decouple adsorption from partitioning contributions or to identify specific non-covalent interaction types at the molecular level. A well-defined model system is therefore necessary to isolate specific interactions from the confounding effects of surface heterogeneity. Fullerene (C60), with its well-defined, stable carbon cage structure and abundant π-electron cloud, provides ~~an~~ a well-defined model system~~ideal model~~ for studying non-covalent interactions at organic compound-particle interfaces (Athar and Patnaik, 2022; Liu and Lu, 2024). By using C60 as a surrogate for carbonaceous aerosol surfaces, one can effectively bypass the complexi-

ties of real particles and systematically examine~~precisely probe~~ the adsorption configurations, energetics, and their regulatory factors. While phenolic compounds may undergo further multiphase aging to form SOA and brown carbon (Pillar-Little and Guzman, 2018; Guzman et al., 2022; Al-Abadleh et al., 2022), the present study focuses on their initial molecular-scale oxidation and interfacial adsorption.

In the complex and dynamic real atmosphere, the transformation of nitrophenols is a dynamic competition among multiple reactive species. The key oxidants include •OH (dominant during daytime), O_3 (with its high background concentration), and •NO_2, which can accumulate at night in polluted regions and initiate non-photochemical nitration pathways (Delaria and Cohen, 2023; Pillar et al., 2014; Yang et al., 2023b). Photolysis of 2,4-DNP has been shown to be a minor loss route compared to •OH oxidation (Albinet et al., 2010~~),~~). •NO_3 radicals represent an additional important component of nighttime phenolic chemistry that is not explicitly included in the present computational framework ~~and while •NO_3-chemistry is an important nighttime pathway for phenols~~(Rana and Guzman, 2022b; Ng et al., 2017). Recent experimental studies have shown that heterogeneous NO_3 oxidation of catechol can generate nitrocatechols, oligomeric products, and light-absorbing brown-carbon chromophores (Rana and Guzman, 2026b), while related studies of phenolic aldehydes further underscore the complexity of heterogeneous nighttime oxidation pathways (Rana and Guzman, 2026a).~~,~~ These studies underscore the importance of NO_3-driven chemistry in the nighttime transformation of phenolic compounds. The present study, however, is restricted to the reaction pathways initiated by O_3, •OH, and •NO_2; therefore, it does not provide a complete

description of the nighttime oxidation chemistry of 2,4-DNP.~~the present study focuses on the thermal oxidation network initiated by O_3, •OH, and •NO_2. These differences in concentrations, reactivities, and reaction mechanisms of these species collectively shape the diverse transformation pathways of nitroaromatics under varying diurnal and pollution regimes.~~

Such multi-pathway transformation processes generate a series of intermediates and final products with diverse chemical properties, which can fundamentally alter the ecological risk profile of nitroaromatic pollutants (Tiwari et al., 2019; Tam et al., 2021). Traditional experimental approaches often struggle to comprehensively identify all reactive intermediates and transformation products, and computational toxicology offers a high-throughput, low-cost alternative for assessing the toxicity of atmospheric transformation products (Tam et al., 2021; Vom Eyser et al., 2013). For instance, for a set of 104 secondary organic aerosol compounds, reliable in silico predictions were obtained for 82 % of the species, whereas experimental data were available for only 13 % (Decesari et al., 2018). Importantly, atmospheric oxidation may produce compounds with toxicity exceeding that of their parents (Vom Eyser et al., 2013), highlighting the need to integrate toxicity prediction into transformation pathway assessment. The application of quantitative structure activity relationship (QSAR) to nitrophenolic transformation products, however, remains limited, and the inherent uncertainties require careful interpretation.

Previous studies on phenolic oxidation have predominantly focused on systems with electron-donating substituents that enhance reactivity. Pillar et al. (Pillar et al.,

2015; Pillar et al., 2014) and Pillar and Guzman (Pillar-Little and Guzman, 2017) demonstrated that catechols and their electron-donating ($–CH_3$, $–OCH_3$) derivatives readily form carboxylic acids, quinones, and polyphenols at interfaces; Rana and Guzman (Rana and Guzman, 2020; Rana and Guzman, 2022b,a) systematically investigated the interfacial oxidation of phenolic aldehydes; Witt et al. (Witt et al., 2025) found that ozonolysis of non-nitrated phenolic aldehydes yields smaller, less toxic molecules such as oxalic and glyoxylic acids; and Rana et al. (Rana et al., 2023) showed that catechol can be converted to 4-nitrocatechol (4NC) in aqueous microdroplets via multiphase $•NO_2/O_3$ chemistry. These studies have laid a foundation for understanding substituent effects, but 2,4-DNP—with two strongly electron-withdrawing nitro groups—may exhibit fundamentally different reactivity and mechanisms.

Despite these advances, a systematic, molecular-level understanding of the multiphase fate of 2,4-DNP remains lacking. Specifically, three core scientific questions need to be addressed: (i) how do the two nitro substituents quantitatively alter the kinetics and selectivity of reactions with O_3, •OH, and $•NO_2$ relative to mononitrophenols? (ii) how does interfacial hydration regulate the adsorption of 2,4-DNP on carbonaceous surfaces at the molecular level? (iii) does oxidative processing of 2,4-DNP detoxify the products, or could it (based on computational predictions) lead to products with higher toxicity?

To answer these questions, this study employs an integrated multiscale theoretical framework combining density functional theory (DFT), molecular dynamics (MD) simulations, and computational toxicology to investigate selected ~~the competing~~ oxidation

and nitration pathways of 2,4-DNP in gas and aqueous phases, its interfacial adsorption behavior on a carbonaceous aerosol surrogate~~s~~ under different hydration conditions, and predicted toxicity indicators of its transformation products. The results provide molecular-level insights into selected transformation pathways and interfacial interactions of 2,4-DNP~~the toxicity evolution of its transformation products. The results provide a molecular-level foundation for a comprehensive assessment of the atmospheric fate and ecological risk of 2,4-DNP~~. This work focuses exclusively on 2,4-DNP as a representative dinitrophenol, and all quantitative conclusions are strictly limited to this compound; however, the qualitative framework established here may serve as a reference for understanding related nitroaromatic systems.

2 Computational methods

2.1 Density functional theory

All density functional theory calculations in this study were performed using the Gaussian 16 software package (Frisch et al., 2016). Geometry optimization, frequency analysis, and single-point energy calculations were conducted for all structures along the reaction pathway, including reactants (Rs), transition states (TSs), intermediates (IMs), and products (Ps), employing the M06-2X functional (Zhao and Truhlar, 2008). To validate the reliability of the chosen basis set, the representative reaction 2,4-DNP + •OH → IM3 was selected, and reaction energies using multiple basis sets were systematically compared, as summarized in Table S1 of the Supplement. The reaction energies ~~The results indicated that the exothermicity~~ computed with different basis sets ~~are~~ were in excellent agreement. Among the tested combinations, the M06-2X/6-

311++G(3df,2p) level yields reaction energies closest to the high-accuracy CCSD(T) benchmark (Spiegel et al., 2024; Nagy, 2024). Considering both computational accuracy and efficiency, the composite method M06-2X/6-31+G(d,p)//6-311++G(3df,2p) was consistently applied in all subsequent calculations. Transition states were located using the TS optimization algorithm and further validated through vibrational frequency analysis and intrinsic reaction coordinate (IRC) calculations (Maeda et al., 2015). Frequency analysis confirmed that all stable structures exhibit no imaginary frequencies, while each transition state possesses exactly one imaginary frequency, consistent with the characteristics of a first-order saddle point, thereby validating the reaction pathway. The IRC trajectories for key transition states are shown in Figure S1. In addition, the solvation model based on density (SMD) (Kromann et al., 2018) was employed to analyze the electronic structures, reactive sites, and free energy changes of key molecules in solvated states.

To gain deeper insights into the ground-state electronic structure and the delocalization characteristics of potential reactive sites, orbital-weighted dual descriptor (OWDD) (Pino-Rios et al., 2019) analysis was conducted using the Multiwfn program (Lu and Chen, 2012). Furthermore, the independent gradient model (IGM) approach was employed to systematically examine both chemical bonding and noncovalent weak interactions within the system (Lefebvre et al., 2017; Lu and Chen, 2022).

2.2 Molecular dynamics simulations

All MD simulations were performed using the GROMACS 2018.8 software package (Van Der Spoel et al., 2005). The simulation system was constructed within a periodic boundary box measuring 30 Å × 30 Å × 60 Å. Each system contained 6 C60 molecules and 15 2,4-DNP molecules, solvated with varying numbers of water molecules (100, 200, 300, and 400), using the explicit SPC/E water model. To construct an idealized gas-aqueous interfacial model~~mimic a realistic aerosol multiphase interface~~, a 20 Å vacuum layer was introduced along the z-axis to create an explicit air-water interface.

The AMBER99SB-ILDN force field was employed for C60 and water molecules, whereas the generalized AMBER force field (GAFF) was used to parameterize 2,4-DNP (Shirts et al., 2003; Wang et al., 2004; Lindorff-Larsen et al., 2010). All topology files were generated with the interactive sobtop program (Lu, 2026). Prior to production runs, each system underwent energy minimization to eliminate unfavorable atomic overlaps. The systems were subsequently equilibrated for 500 ps in the NVT ensemble at 298.15 K with a 2 fs integration time step, followed by production MD simulations of 1 ns for data collection and analysis. All molecular visualizations and trajectory analyses were performed using the VMD software (Humphrey et al., 1996).

2.3 Kinetic calculations

The rate constants for the primary reactions were calculated using the thermodynamic formulation of the conventional transition state theory (TST) (Tuñón and Williams, 2019) with support from the KISthelp tool (Canneaux et al., 2014) and TST calculator (Lu, 2025), as represented by the following equation:

$$k^{TST}=\sigma * k_B T/h * e^{-\Delta G\neq/(k_B T)} \quad (1)$$

where σ is the reaction path degeneracy, k_B is the Boltzmann constant, T is the temperature, and h is Planck's constant. $\Delta G^{\neq}$ represents the standard Gibbs free energy of activation for the considered reaction. For reaction path simplicity, the following equation is followed:

$$\sigma = \sigma_{rot,\ R} / \sigma_{rot,\ TS} \quad (2)$$

where $\sigma_{rot,\ R}$ and $\sigma_{rot,\ TS}$ are rotational symmetry numbers of reactants and transition states (for N molecule reactions, $\sigma_{rot,\ R}$ is the product of the rotational symmetry numbers of all the reactants); σ is generally 1 for reactions of macromolecular systems.

2.4 Computational toxicology

The toxicological profiles of 2,4-DNP and its atmospheric transformation products were characterized through a hierarchical QSAR strategy (Young et al., 2008). Key toxicity endpoints, including Ames mutagenicity (Sushko et al., 2010) and developmental toxicity (Cassano et al., 2010), were predicted using the Toxicity Estimation Software Tool (T.E.S.T.) version 5.1.2 developed by the U.S. Environmental Protection Agency (Epa, 2020). All predictions were subjected to applicability domain verification based on descriptor leverage analysis, and only data for compounds falling within the chemical space defined by the training set were retained to ensure the statistical validity and reliability of subsequent comparative toxicological analyses (Benfenati et al., 2009).

3 Results and discussion

3.1 Reaction mechanisms of 2,4-DNP with O_3, •OH, and •NO_2 in the gas and aqueous phases

Establishing the stable molecular configuration and regional reactivity of 2,4-DNP is essential for understanding the initial reaction mechanisms with O_3 (an electrophile), •OH (a radical), and •NO_2 (which exhibits both electrophilic and radical characteristics). Such characterization provides critical theoretical insights into the distinct mechanistic origins of these reaction processes. To elucidate the fundamental reaction pathways and selectivity differences of 2,4-DNP with various reactants in multiphase environments, this study initiates a theoretical characterization of its ground state, including its electronic structure and reactive sites.

3.1.1 Characterization of the electronic structure of 2,4-DNP

Based on geometric optimization and electronic structure calculations, the stable conformation of 2,4-DNP and its reactive sites analysis are shown in Figure 1. The global minimum energy conformation stabilized by intramolecular hydrogen bonding is presented in Figure 1a, while the OWDD isosurface in Figure 1b clearly delineates the nucleophilic and electrophilic reaction regions of the molecule, thus providing a robust theoretical foundation for elucidating the subsequent reaction mechanisms.

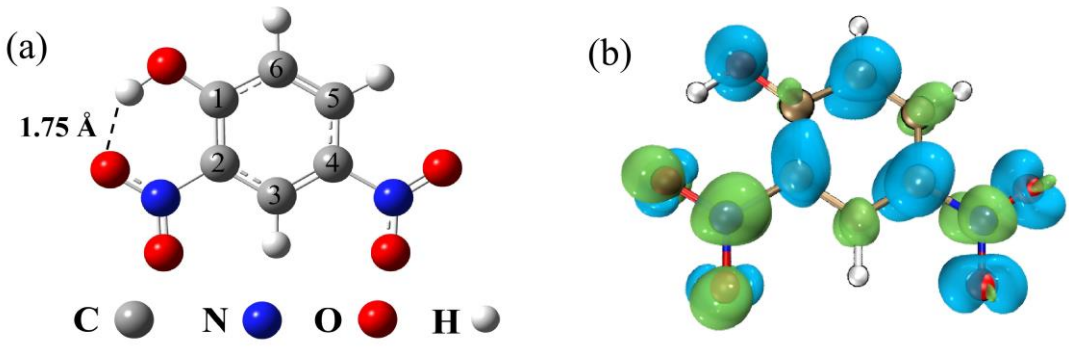


Figure 1 (a) The most stable configuration of 2,4-DNP, stabilized by intramolecular hydrogen bonding. (b) Isosurface of the OWDD for 2,4-DNP, where blue and red regions denote nucleophilic and electrophilic sites, respectively.

The global minimum energy conformation of 2,4-DNP is depicted in Figure 1a. The exceptional stability of this structure arises primarily from the synergistic effects of intramolecular hydrogen bonding and π-electron delocalization. Structural analysis reveals ~~indicates that~~ a strong intramolecular hydrogen bond (O–H···O_2N–) between the hydroxyl group and the ortho-positioned nitro group (position 2), with an H···O distance of 1.75 Å, ~~—~~a value ~~s~~ characteristic of strong intramolecular hydrogen ~~bonds~~ bonding (1.6–1.9 Å)(Steiner, 2002). This interaction forms a stable, planar six-membered ring motif that benefits from both the hydrogen bond and the rigidity of the aromatic ring. Additionally, both the ortho- and para-nitro groups (at positions 2 and 4, respectively) adopt nearly coplanar orientations relative to the benzene ring, with dihedral angles of 178.30° and 179.67°, approaching the ideal 180° for maximum orbital overlap. This coplanarity enables effective π–π conjugation with the aromatic system and further enhances the overall molecular stability (Szatylowicz et al., 2017). Importantly, these two stabilizing factors are mutually reinforcing: the hydrogen bond locks the ortho-nitro group into the plane, facilitating conjugation, while the enhanced conjugation further polarizes the nitro group, strengthening the hydrogen bond.

As shown in Figure 1b, the OWDD isosurface analysis (Δfω) reveals well-defined regional chemical features of the 2,4-DNP. Blue regions ($\Delta f\omega < 0$) are localized around specific carbon atoms on the benzene ring and the hydroxyl oxygen atom, indicating

~~sites~~ electron-rich sites that are susceptible to electrophilic attack. These electron-rich sites arise from the electron-donating effect of the hydroxyl group, which concentrates electron density at the ortho and para positions relative to the nitro groups. In contrast, green regions ($\Delta f\omega > 0$) are mainly located at the outer ends of the oxygen and nitrogen atoms in the nitro and hydroxyl groups, showing electron-poor sites that are susceptible to nucleophilic attack, which arise from the polarization of N–O bonds. This electronic structure feature provides a reliable basis for predicting its reactivity toward various atmospheric oxidants. As a strong electrophile, O_3 preferentially targets the electron-rich carbon atoms (blue regions), initiating electrophilic addition at the sites with the highest nucleophilic character. Meanwhile, ~~•OH displays dual reactivity: it adds to nucleophilic blue regions on the benzene ring, while also abstracting hydrogen atoms from weakly electrophilic sites such as the C–H bonds (adjacent to nitro groups) or the hydroxyl hydrogen, which correspond to regions of weaker Δfω positive values. Similarly, •NO_2, possessing both radical and electrophilic characteristics, displays dual reactivity, participating either in radical addition to nucleophilic carbons or in hydrogen abstraction reactions, with its preference modulated by the local Δfω distribution.~~•OH and •NO_2 can participate in both ring addition and hydrogen-abstraction reactions. However, the preferred HAA sites cannot be inferred solely from the ground-state Δfω distribution and are evaluated explicitly from the calculated reaction energetics below.

3.1.2 Primary reactions of 2,4-DNP with O_3, •OH, and •NO_2

Based on the analysis of nucleophilic and electrophilic sites in the electronic structure of 2,4-DNP, this section systematically elaborates the primary reaction pathways of 2,4-DNP with O_3, •OH, and •NO_2. The competition among different channels is elucidated through thermodynamic and kinetic calculations, thereby characterizing the selected transformation pathways examined in this study~~revealing transformation mechanisms of 2,4-DNP in the atmosphere~~.

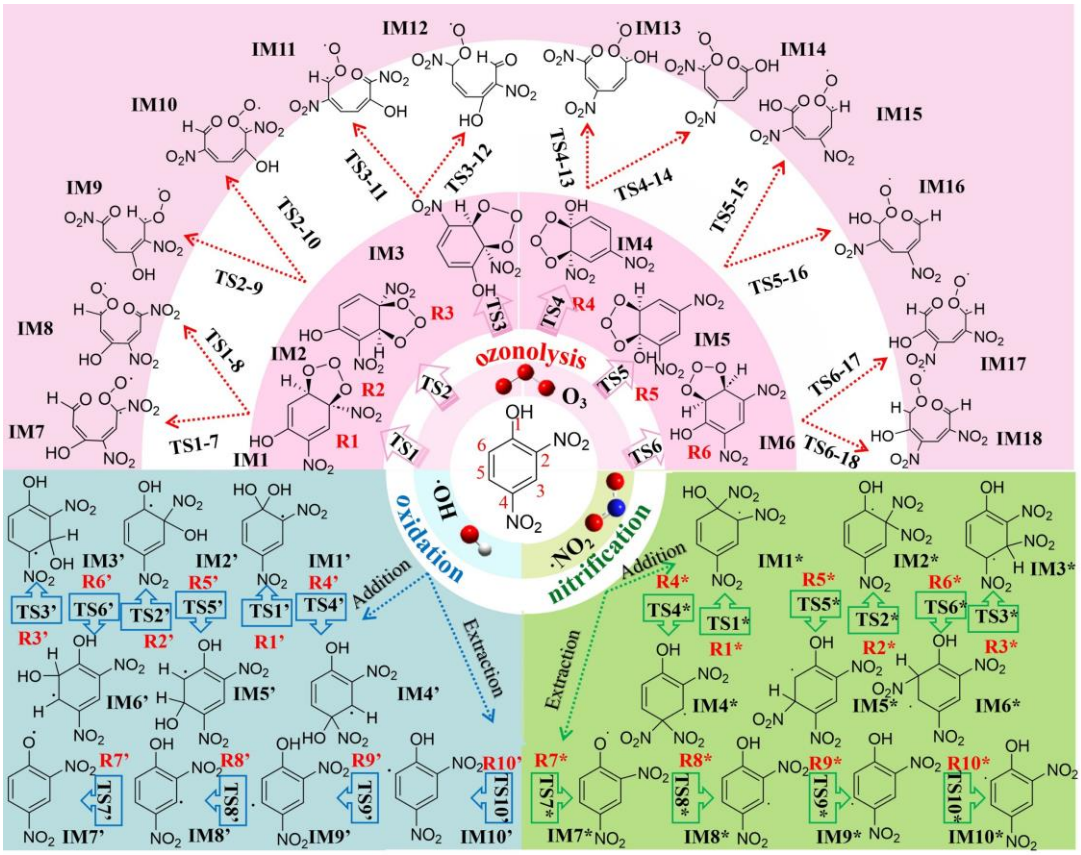


Figure 2 Proposed initial reaction mechanisms of 2,4-DNP with O_3, •OH, and •NO_2.

The coexistence of an electron-donating hydroxyl group and strong electron-withdrawing nitro groups in the 2,4-DNP induces a highly polarized and asymmetric distribution of π-electron density in the benzene ring (Li et al., 2023). This distinct electronic structure directly governs the pronounced regioselectivity of its reactions with O_3, •OH, and •NO_2.

As a typical 1,3-dipole, ozone can attack the electron-rich aromatic π-system via cycloaddition. Calculations indicate that among the six possible 1,3-dipolar cycloaddition pathways, the reaction preferentially occurs at the C5–C6 bond located between the hydroxyl and nitro groups, as indicated by the red region in Figure 2. The reaction proceeds via transition state TS6, in which the terminal oxygen atoms of O_3 simultaneously approach the C5 and C6 atoms, accompanied by significant elongation of the original C5–C6 bond (optimized geometries are compiled in Table S2), indicating irreversible disruption of aromatic stabilization. This step represents the most favorable reaction pathway. Subsequently, the resulting unstable primary ozonide (POZ) intermediate IM6 undergoes concerted dissociation via transition state TS6-17, leading to the formation of the vibrationally excited Criegee intermediate (CI) IM17, which is energetically the most favorable product.

The reaction of 2,4-DNP with •OH mainly proceeds through two competing mechanisms, namely ring addition and HAA, as shown in the blue region of Figure 2. In the electrophilic addition pathway, •OH preferentially attacks the C3 site, which is located between the two nitro groups and is meta to the hydroxyl substituent. This process proceeds through transition state TS3', in which the •OH oxygen approaches C3 with significant shortening of the forming bond distance, accompanied by elongation of the adjacent C2–C3 and C3–C4 bonds– and a geometry that facilitates effective overlap between the p-orbital of •OH and the π-system of the benzene ring, thereby ultimately yielding the hydroxy-cyclohexadienyl radical intermediate IM3'. In the HAA pathway,

384 •OH primarily captures the H atom directly bonded to the C5 site. This reaction pro-
385 ceeds through transition state TS9', characterized by a nearly linear O–H–C5 arrange-
386 ment, which is characteristic of a hydrogen abstraction transition state. This step pro-
387 duces the phenoxy radical intermediate IM9' and one molecule of H_2O. Notably, the
388 OWDD analysis indicates that the carbon at C5 is an electron poor site, which is sus-
389 ceptible to nucleophilic attack. This appears contrary to the conventional expectation
390 that an electrophilic radical such as •OH would preferentially abstract a hydrogen atom
391 from an electron rich site. However, the HAA reaction of •OH is governed primarily
392 by C–H bond dissociation energies (BDEs) rather than ground state electron density
393 (Mayer, 2011). ~~The C5–H bond is significantly weakened by the electron withdrawing~~
394 ~~effect of the adjacent nitro group, making it the preferred abstraction site despite its low~~
395 ~~electron density.~~ The preference for C5 abstraction is therefore more appropriately in-
396 terpreted in terms of the calculated reaction energetics and transition-state structure ra-
397 ther than the ground-state electron-density distribution alone.

398 ~~•NO_2 is primarily a radical species with only weak electrophilic character. Its ad-~~
399 ~~dition to the ring is therefore not simply governed by electrophile–nucleophile interac-~~
400 ~~tions, but rather by radical stability and transition-state polar effects.~~

401 The reaction of •NO_2 with 2,4-DNP proceeds via two competing pathways,~~:~~ radi-
402 cal addition and HAA, as shown in the green region of Figure 2. Although the reaction
403 pathways of 2,4-DNP with •NO_2 and •OH both involve radical addition and hydrogen
404 abstraction~~two fundamental elementary steps~~, significant differences are observed~~exist~~

in their reactivity and pathway selectivity. In the radical addition pathway, •NO_2 preferentially attacks the C3 site via transition state TS3*, leading to the formation of the nitrocyclohexadienyl radical intermediate IM3*. ~~This reaction mode resembles the •OH addition process, suggesting some consistency in regioselectivity.~~ This regioselectivity is similar to that calculated for •OH addition. However, unlike O_3 and •OH, whose reactivities sites show a clearer relationship with the Δfω distribution, •NO_2 has only weak electrophilic character, and its addition pathway cannot be interpreted solely in terms of electrophile–nucleophile interactions. Radical stabilization and transition-state effects may also contribute to the calculated regioselectivity~~are well correlated with the Δfω distribution, •NO_2 is primarily a radical species with only weak electrophilic character. Its addition to the ring is therefore not simply governed by electrophile–nucleophile interactions, but rather by radical stability and transition-state polar effects. The HAA pathway displays markedly different behavior~~. The HAA pathway exhibits different site selectivity. Whereas •OH preferentially abstracts the C5-bound hydrogen in the gas phase, the lowest-energy HAA channel identified for •NO_2 involves abstraction of the C6-bound hydrogen through transition state TS10*. Nevertheless, this preference should be distinguished from the overall kinetic feasibility of the pathway. The calculated gas-phase barrier for C6 hydrogen abstraction by •NO_2 is 41.39 kcal mol^{-1}, substantially higher than the 18.48 kcal mol^{-1} barrier for the competing C3-addition pathway. Thus, although C6 is the preferred H-abstraction site among the investigated direct •NO_2 HAA channels, direct HAA by •NO_2 remains kinetically unfavorable for parent 2,4-DNP.~~Unlike •OH, which mainly abstracts hydrogen atoms from~~

~~the C5 site, $•NO_2$ preferentially abstracts the hydrogen atom of the hydroxyl group through transition state TS7*. This difference originates from the fundamentally different reaction characteristics of the two radicals. The high reactivity of •OH allows it to overcome unfavorable ground-state electrostatics and abstract the H atom at C5. By contrast, $•NO_2$ has much weaker electrophilicity and lower reactivity; its hydrogen abstraction depends on electrostatic complementarity and charge transfer, and it preferentially targets the hydroxyl hydrogen(Shenghur et al., 2014). Moreover, the $•NO_2$-mediated hydrogen abstraction is often accompanied by substantial charge transfer, with a mechanism that more closely resembles proton-coupled electron transfer (PCET)(Tyburski et al., 2021). In 2,4-DNP, the intramolecular hydrogen bond between the hydroxyl group and the ortho-nitro group significantly weakens the O–H bond, lowering its bond dissociation energy, which further favors hydroxyl hydrogen abstraction by $•NO_2$.~~

(a)

	Gas		Aqueous	
	$\Delta E^{\ddagger}$	ΔE	$\Delta G^{\ddagger}$	ΔG
TS6	10.12	−35.56	11.62	−37.23
TS5	12.58	−28.66	14.51	−28.37
TS4	15.23	−29.55	18.09	−27.02
TS3	15.10	−29.29	17.92	−27.83
TS2	10.88	−32.91	13.89	−31.66
TS1	16.60	−22.67	19.85	−22.51

(b)

	Gas		Aqueous	
	$\Delta E^{\ddagger}$	ΔE	$\Delta G^{\ddagger}$	ΔG
TS10	5.43	−2.49	16.01	−4.20
TS9	4.70	−3.46	16.20	−5.72
TS8	8.45	−1.22	19.87	−4.11
TS7	9.22	−12.42	12.90	−18.79
TS6	3.14	−19.51	11.98	−8.87
TS5	5.17	−18.56	13.72	−7.44
TS4	3.84	−21.71	14.39	−9.51
TS3	2.84	−18.28	14.37	−11.60
TS2	2.96	−19.00	14.00	−10.31
TS1	5.63	−17.20	15.54	−7.64

(c)

	Gas		Aqueous	
	$\Delta E^{\ddagger}$	ΔE	$\Delta G^{\ddagger}$	ΔG
TS10	41.39	35.59	50.04	31.68
TS9	41.85	34.62	50.89	30.17
TS8	45.73	36.86	55.54	31.77
TS7	49.11	26.91	58.31	18.61
TS6	19.54	17.86	27.85	25.43
TS5	20.31	19.34	28.90	25.89
TS4	24.38	23.31	34.35	33.36
TS3	18.48	17.69	26.55	23.44
TS2	25.95	25.59	36.60	36.03
TS1	23.42	23.19	32.42	30.86

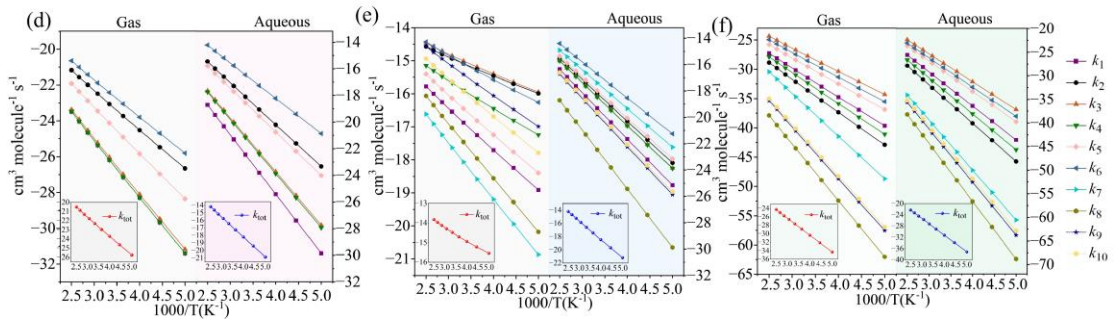


Figure 3 Thermodynamics, kinetics, and temperature dependence of the reactions of 2,4-DNP with O_3, •OH, and •NO_2. (a–c) reaction energy barriers ($\Delta E^{\neq}$) and reaction energies ($\Delta_r E$) for the key pathways (unit: kcal mol^{-1}). (d–f) intrinsic temperature-dependent reaction rate constants for the major channels.

The combined thermodynamic and kinetic analysis reveals that the reaction of O_3 with 2,4-DNP is both thermodynamically favorable and kinetically accessible in the gas and aqueous phases. As shown in Figure 3a, the most favorable gas-phase pathway, R6, has a low energy barrier of 10.12 kcal mol^{-1} and is strongly exothermic ($\Delta_r E$ = –35.56 kcal mol^{-1}). In the aqueous phase, although the barrier increases moderately to 11.62 kcal mol^{-1}, the reaction remains significantly exothermic. This indicates that solvation does not fundamentally alter the thermodynamic driving force, and the calculated ~~relatively low~~ barrier remains moderate within the present ~~ensures that the reaction remains kinetically~~ reaction framework ~~feasible in both environmental media~~. In contrast, the reaction of 2,4-DNP with •OH shows even more favorable calculated kinetics than the O_3 and direct •NO_2 reactions examined here ~~kinetics, consistent with its role as the major atmospheric oxidant~~. The addition pathway in the gas phase proceeds with an exceptionally low barrier of 2.84 kcal mol^{-1}, substantially lower than the O_3- initiated pathway, as presented in Figure 3b. The HAA pathway also presents a low barrier of 4.70 kcal mol^{-1}. The similar barrier heights suggest that both ~~these two •OH-initiated~~ pathways ~~are~~ may be kinetically competitive ~~and~~ at the molecular level ~~are expected to occur concurrently under atmospheric conditions~~. By comparison, the direct reaction of 2,4-

DNP with •NO_2 is much less favorable. The overall process is endothermic and thermodynamically less favorable within the calculated energy framework, as illustrated in Figure 3c. Among the two plausible direct reaction pathways, radical addition to the aromatic ring via the nitration pathway R3* has a calculated energy barrier of 18.48 kcal mol^{-1}, whereas HAA pathway has an even higher barrier of 41.39 kcal mol^{-1}, making it far less accessible. Although the nitration channel is kinetically favored over HAA in the •NO_2 system, its energy barrier is still ~~great~~much higher than those of the corresponding •OH-initiated pathways and is also less thermodynamically favorable than both •OH- and O_3-mediated reactions.

Given these pronounced kinetic limitations, combined with the typically lower atmospheric concentration of •NO_2 relative to •OH and O_3, the calculations might suggest that •NO_2 reactivity is negligible ~~combined with the typically lower atmospheric concentration of •NO_2 relative to •OH and O_3, the calculations might suggest that •NO_2 reactivity is negligible~~ (Shi et al., 2025; Chapleski et al., 2016). To distinguish the different roles of •NO_2 within the reaction framework examined here it is useful to distinguish three distinct levels of •NO_2 involvement in the atmospheric chemistry of 2,4-DNP, a distinction that has been emphasized in recent multiphase studies ~~However, to provide a complete picture, it is useful to distinguish three distinct levels of •NO_2 involvement in the atmospheric chemistry of 2,4-DNP, a distinction that has been emphasized in recent multiphase studies~~(Rana et al., 2023). Level (i) is the direct reaction of •NO_2 with the parent compound 2,4-DNP, which ~~we have shown~~shows substantially lower calculated reactivity than the •OH pathway~~to be kinetically negligible even~~ under

the concentration scenarios considered here~~nighttime conditions (see pseudo-first-order analysis below)~~. ~~–~~Level (ii) is the reaction of •NO_2 with primary oxidation intermediates such as IM3' (Section 3.1.3), which exhibits a remarkably low barrier of 2.01 kcal mol^{-1} for HAA, indicating that this indirect •NO_2 pathway is mechanistically feasible. However, its atmospheric contribution depends on competition with O_2 and other reactants, as discussed in Section 3.1.3. Level (iii) is the multiphase •NO_2/O_3 chemistry in aerosol water or microdroplets, where •NO_2 can participate through N_2O_4 uptake and hydrolysis, leading to nitration via NO_2^+ or NO^+ species (Rana et al., 2023). This multilevel distinction clarifies that, although ~~while~~ the direct reaction of •NO_2 with parent 2,4-DNP is kinetically unfavorable in the investigated scenarios~~negligible~~, the indirect pathways involving •NO_2 and oxidized intermediates or multiphase processes represent additional mechanisms within the present reaction framework~~may still be environmentally relevant~~. These pathways should not be considered a complete description of nighttime reactive-nitrogen chemistry because direct NO_3 oxidation was not included in the present calculations. ~~The possible involvement of •NO_2 in subsequent reactions with primary oxidation intermediates (Level ii) will be discussed separately in Section 3.1.3 to provide a complete mechanistic picture.~~

This study further shows that the reaction behavior of 2,4-DNP in the aqueous phase differs markedly from that in gas phase and from that of simpler nitrophenol analogues. This difference is fundamentally attributed to the restructuring of molecular electronic distribution and reaction coordinates by the dynamic hydrogen-bonding net-

work established between water and 2,4-DNP (Lyu et al., 2025). In contrast to the common trend in which solvation stabilizes polar transition states and thus lowers energy barriers in mononitrophenols, 2,4-DNP exhibits the distinctive features of increased aqueous-phase energy barriers and solvent-induced switching of regioselectivity.

The increase in the calculated aqueous-phase ~~energy~~ barriers can be attributed to changes in the balance between intramolecular and solute-solvent interactions upon solvation~~the disruptive effect of the solvent on the intramolecular cooperativity inherent to 2,4-DNP~~. The simultaneous presence of the ~~a strongly electron-donating~~ hydroxyl group and ~~strongly electron-withdrawing~~ nitro substituents produces pronounced electronic polarization~~groups induces a pronounced intramolecular electric field~~, while the ortho-substitution pattern enables intramolecular hydrogen bonding ~~geometry further enables stabilizing intramolecular hydrogen bonds~~(Albinet et al., 2010). These structural features provide significant ground-state stabilization in the gas phase. In aqueous solution, water molecules interact with the polar functional groups and compete with the intramolecular hydrogen-bonding network, thereby altering the relative stabilization of the reactant and transition-state structures (Yang et al., 2023a). Solvent reorganization may also contribute to the calculated free-energy barrier. Consequently, the overall barrier depends on the relative solvation of the reactant and transition state and can therefore increase for the pathways considered here. The change in site selectivity likewise arises from solvent-mediated electron redistribution and pathway switching. In the ring-addition pathway of •OH, the C3 position is more favorable in the gas phase because of the dominant conjugation effects. In the aqueous phase, however, water

molecules enhance the local polarization near the hydroxyl-adjacent carbon C6, making another site more competitive for attack. ~~For hydrogen abstraction reactions, the gas-phase pathway is associated with C – H bond dissociation energetics, where the C5 – H bond is weakened by the adjacent nitro group and is therefore more susceptible to homolysis. In the aqueous phase, the calculated pathway exhibits increased proton-transfer character. The hydroxyl hydrogen, due to its intrinsic acidity and the proton-transfer assistance provided by the hydrogen-bonding network of water, gains both kinetic and thermodynamic advantages, becoming the dominant abstraction site in solution.~~For the •OH HAA pathways, the preferred abstraction site also changes upon solvation. In the gas phase, abstraction from C5 is favored among the investigated HAA channels, whereas in the aqueous phase the hydroxyl hydrogen becomes more favorable in the calculated pathway. This change suggests that solvation modifies the relative energetics of the competing H-abstraction sites, likely through differential stabilization of the reactant and transition-state structures. In contrast, the preferred HAA channel identified for •NO_2 involves abstraction from C6 in both phases, although this pathway remains kinetically unfavorable because of its high calculated barriers.

Kinetic calculations further quantify the feasibility differences among various pathways under atmospheric conditions. To ensure physical significance and environmental interpretability, all rate constants were converted into the standard unit commonly used in atmospheric chemistry (cm^3 $molecule^{-1}$ s^{-1}). Aqueous-phase data were

converted from their original units of M^{-1} s^{-1} using the Avogadro constant and volume-unit conversion (1 M^{-1} s^{-1}= (1000/NA) cm^3 $molecule^{-1}$ s^{-1}≈ 1.66 × 10^{-21} cm^3 $molecule^{-1}$ s^{-1}).

Table 1 Calculated energy barriers ($\Delta E^{\neq}$, kcal mol^{-1}), reaction energies ($\Delta_r E$, kcal mol^{-1}), and rate constants (*k*tot, cm^3 molecule^{-1} s^{-1}) at 298.15 K for the representative reaction channels of 2,4-DNP with O_3, •OH, and •NO_2 in the gas and aqueous phases. "—" indicates that the rate constant was not calculated because the corresponding pathway is kinetically insignificant (Complete rate constant data for all channels are provided in Table S3). *k*tot at 298.15 K for each oxidant is the sum of all contributing channels for that oxidant.

Oxidant	Channel	Phase	$\Delta E^{\neq}$	$\Delta_r E$	*k*tot (298 K)
O_3	R6 (C5=C6 addition)	Gas	10.12	–35.56	4.23×10^{-23}
		Aq.	11.62	–37.23	3.17×10^{-17}
•OH	R3' (addition at C3)	Gas	2.84	–18.28	3.18×10^{-15}
	R6' (addition at C6)	Aq.	11.98	–8.87	2.25×10^{-17}
	R9' (HAA at C5)	Gas	4.70	–3.46	—
	R7' (HAA at OH)	Aq.	12.90	–18.79	—
•NO_2	R3* (addition at C3)	Gas	18.48	17.69	1.75×10^{-28}
		Aq.	26.55	23.34	3.93×10^{-28}
	R10* (HAA at C6)	Gas	41.39	35.59	—
		Aq.	50.04	31.68	—

As shown in Figure 3d–f, the rate constants of all major channels increase with temperature over the range of 200–400 K, exhibiting ~~a characteristic~~ Arrhenius-type temperature dependence. The total rate constants of the dominant pathways at 298.15 K are compiled in Table 1.~~,~~ Among the reactions examined, the •OH pathway shows

the highest calculated gas-phase rate coefficient, ~~which summarizes the thermodynamic and kinetic data for O_3, •OH, and •NO_2 in both gas and aqueous phases. Several trends are evident from these data. The •OH pathway shows the highest kinetic activity,~~ with total gas-phase and aqueous-phase rate constants of 3.18×10^{-15} cm^3 $molecule^{-1}$ s^{-1} and 2.25×10^{-17} cm^3 $molecule^{-1}$ s^{-1}, respectively~~, at 298.15 K,. further confirming its role as the dominant atmospheric oxidant.~~ The O_3 pathway also shows a calculated aqueous-phase rate coefficient ~~notable activity in the aqueous phase, with a total aqueous-phase rate constant~~ of 3.17×10^{-17} cm^3 $molecule^{-1}$ s^{-1}, indicating appreciable intrinsic reactivity in the aqueous phase~~highlighting the importance of aqueous environments in multiphase chemistry~~. In contrast, the direct •NO_2 pathway is kinetically unfavorable~~exhibits extremely low kinetic activity~~, with calculated~~total~~ gas-phase and aqueous-phase rate constants ~~as low as~~of 1.75×10^{-28} cm^3 $molecule^{-1}$ s^{-1} and 3.93×10^{-28} cm^3 $molecule^{-1}$ s^{-1}, respectively. ~~These values are more than 13 orders of magnitude lower than those of the •OH pathway. Even under conditions of elevated •NO_2 concentration, the contribution of this pathway to the transformation of 2,4-DNP is expected to be negligible.~~ These bimolecular rate coefficients describe the intrinsic reactivity of the investigated pathways, but do not by themselves determine their atmospheric importance, which also depends on oxidant concentrations and phase partitioning. To examine whether the very low intrinsic reactivity of the direct •NO_2 pathway could be offset by nighttime •NO_2 accumulation, pseudo-first-order rate coefficients were estimated under illustrative scenarios based on literature-reported oxidant concentrations.

~~It should be emphasized that the trends described above, however, reflect only the intrinsic molecular reactivity of each oxidant; their actual atmospheric importance depends on oxidant concentrations, phase partitioning, and aerosol liquid water content. To bridge this gap between intrinsic reactivity and atmospheric relevance, pseudo-first-order rate constants were estimated using literature-reported oxidant concentrations. These estimates are presented below, providing a more realistic assessment of the relative contributions of each pathway under typical tropospheric conditions.~~

The literature review indicates that •OH concentrations typically reach $1 \times 10^6 \sim 3 \times 10^6$ molecules cm^{-3}, while $•NO_2$ is rapidly photolyzed during daytime~~levels are lower due to rapid photolysis under daytime conditions~~. Under~~During heavily~~ polluted nighttime conditions, however, •OH concentrations drop substantially~~–~~. Geyer et al. (Geyer et al., 2003) reported a nocturnal •OH concentration of $(1.85 \pm 0.82) \times 10^5$ molecules cm^{-3} during the BERLIOZ campaign, while nighttime •OH concentrations ~~and in UK urban surface environments, night-time OH levels were determined to be in the range~~ of $10^5 \sim 10^6$ molecules cm^{-3} have been reported in UK urban surface environments (Khan et al., 2011). In contrast~~Meanwhile~~, $•NO_2$ can accumulate significantly at night, with nocturnal maxima reaching 8.43 ± 0.4 ppb in Guangzhou (Qin et al., 2009). Using these literature-reported concentrations as illustrative nighttime scenarios, the pseudo-first-order rate constants ~~under nighttime conditions can be estimated. For~~for the •OH pathway is estimated to be approximately $10^{-10} \sim 10^{-9}$ s^{-1}, ~~with~~ based on k_{OH} = 3.18×10^{-15} cm^3 $molecule^{-1}$ s^{-1} ~~and [OH] ≈ 10^5 – 10^6 molecules cm^{-3}, $k'_{OH} \approx 10^{-10} \sim 10^{-9}$ s^{-1}~~. In contrast, for~~For~~ the direct $•NO_2$ pathway, a bimolecular rate coefficient

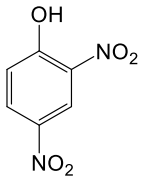
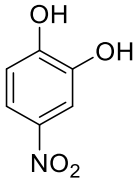
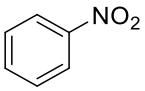
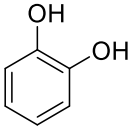
ofwith $k_{NO2} \approx 10^{-28}$ cm^{3}-^{3} molecule^{-1} s^{-1} combined with a nighttime •NO_2 concentration of several ppb, yields a pseudo-first-order rate coefficientand on the order of [NO_2] ≈ 10^{10} – 10^{11} molecules cm^{-3} (corresponding to 0.4 – 4 ppb at 298 K and 1 atm), $k'NO_2$ ≈ 10^{-18} – 10^{-17} s^{-1}. Therefore, under the illustrative nighttime conditions considered here, the direct •NO_2 pathway remains more than seven orders of magnitude slower than the •OH pathway and is unlikely to compete effectively with •OH oxidation. Importantly, these estimates compare only the investigated bimolecular reaction channels and do not represent the overall atmospheric lifetime of 2,4-DNP, which would also depend on photolysis, deposition, phase partitioning, heterogeneous chemistry, and other loss processesThus, under the illustrative nighttime conditions considered here, the direct •NO_2 pathway remains more than seven orders of magnitude slower than the •OH pathway and is unlikely to compete effectively with •OH oxidation.. The aqueous-phase calculations further indicate appreciable intrinsic reactivity toward O_3. Accordingly, the relative contributions of the investigated pathways to the overall atmospheric loss of 2,4-DNP cannot be quantified without additional information on phase partitioning and more comprehensive atmospheric chemistry modelingAccordingly, the relative contributions of the investigated pathways to the overall atmospheric loss of 2,4-DNP cannot be quantified without additional partitioning information and atmospheric chemical modeling. The possible involvement of •NO_2 in subsequent reactions with primary oxidation intermediates is discussed separately below.Even under the most favorable nighttime conditions (lowest •OH, highest •NO_2), the direct •NO_2 pathway remains more than 7 orders of magnitude slower than the •OH pathway, corresponding to a

~~lifetime of >10^{10} s, which is negligible on atmospheric timescales. Therefore, while a full diurnal box model simulation would be required to quantify all pathways under varying pollution regimes, the quantitative analysis above confirms that the direct reaction of •NO_2 with parent 2,4-DNP is negligible even under nighttime conditions. The possible involvement of •NO_2 in subsequent reactions with primary oxidation intermediates will be discussed separately to provide a complete mechanistic picture of its environmental fate. In summary, the atmospheric degradation of 2,4-DNP is kinetically dominated by •OH, with O_3 playing a significant role in the aqueous phase, while the direct transformation contribution of •NO_2 can be neglected in environmental assessments.~~

The atmospheric~~overall~~ contribution of aqueous-phase reactions ~~to the atmospheric fate of 2,4-DNP~~ additionally also depends on the fraction of 2,4-DNP present in~~depends critically on the fraction of the compound that partitions into~~ the aqueous phase. ~~For 2,4-DNP, the~~The Henry's law constant for 2,4-DNP has been reported ~~determined~~ as 5.70 × 10^{-8} atm·m^3/mol at 5 °C (Lüttke and Levsen, 1997)~~,~~. ~~It~~~~indicating a strong tendency to partition into the aqueous phase. The partitioning is further modulated by it~~s acid dissociation constant (pKa ≈ 4.09 at 25 °C)~~,~~ further affects aqueous partitioning because the deprotonated form is more water-soluble than the neutral species ~~as the deprotonated phenolate form is substantially more water-soluble than the neutral phenol~~(Schwarzenbach et al., 1988). ~~In addition, the a~~Aerosol liquid water content ~~— which varies widely depending on relative humidity, particle composition, and atmospheric conditions —~~ also determines the ~~available~~ aqueous volume available for

multiphase reactions. Without quantitative information on these partitioning parameters under specific atmospheric conditions, the aqueous-phase rate constants should be interpreted as intrinsic reactivity indicators rather than direct measures of atmospheric importance.

Table 2 The experimental rate constant (cm^3 $molecule^{-1}$ s^{-1}) values of various phenols with O_3 in the gas phase.

Compound	Structure formula	Rate constants (cm^3 $molecule^{-1}$ s^{-1})
2,4-DNP		4.23×10^{-23}
4-Nitrocatechol		1.48×10^{-20} (Wang et al., 2026)
Nitrobenzene		$(7.00 \pm 0.20) \times 10^{-21}$ (Atkinson et al., 1987)
Catechol		$(9.60 \pm 1.12) \times 10^{-18}$ (Sun et al., 2022; Tomas et al., 2003)

The calculated rate coefficients were further compared with ~~constants are further validated through systematic benchmarking against~~ available experimental and computational data for structurally related aromatic compounds, as summarized in Table 2 and Table S4. Although direct experimental measurements for this specific reaction are currently unavailable, the theoretical rate constant for the mononitro analogue nitrocatechol (1.48×10^{-20} cm^3 $molecule^{-1}$ s^{-1}) (Wang et al., 2026) is approximately three orders of magnitude lower than that of catechol (Sun et al., 2022; Tomas et al., 2003), consistent with a strong deactivating ~~clearly demonstrating the strong inhibitory~~ effect of the nitro group, as an electron-withdrawing functional group on the ozone reactivity of the aromatic ring. Building on this trend, the calculated rate constant for the dinitro compound 2,4-DNP (4.23×10^{-23} cm^3 $molecule^{-1}$ s^{-1}) is reduced by an additional three

orders of magnitude, quantitatively reflecting the cumulative electron-withdrawing effect of the two nitro substituents. This trend is consistent with the established understanding of substituent effects in phenolic oxidation: electron-donating groups such as $–CH_3$ and $–OCH_3$ enhance reactivity (Pillar et al., 2014; Pillar et al., 2015; Pillar-Little and Guzman, 2017; Rana and Guzman, 2020), while electron-withdrawing nitro groups deactivate the aromatic ring toward electrophilic attack.

Furthermore, the predominance of substituent electronic effects in governing reactivity is independently corroborated. As detailed in Table S4, a systematic comparison of the theoretical rate constants for the reaction of 2,4-DNP with •OH with data for structural analogues demonstrates that the strong electron-withdrawing character of the nitro groups likewise controls the kinetics of this pathway. This consistency suggests that the electronic influence of nitro substituent is general across different oxidants rather than being restricted to a single mechanism. ~~Collectively, these results establish a robust and quantitatively consistent framework for predicting the atmospheric oxidation kinetics of aromatic pollutants on the basis of their fundamental electronic structure.~~Collectively, these comparisons support the qualitative role of electron-withdrawing nitro substituents in modulating the calculated reactivity of 2,4-DNP and related nitroaromatic compounds.

3.1.3 The subsequent reactivity mechanism of the key intermediate IM3’

Among the initiation pathways examined here, •OH addition ~~As the primary initiator of atmospheric degradation of 2,4-DNP, •OH~~ generates the key radical intermediate IM3' via electrophilic addition. This highly reactive species can rapidly undergo secondary reactions with surrounding atmospheric constituents. The following calculations examine selected secondary reactions of IM3' with O_2 and •NO_2. These reactions were considered to evaluate the relative energetics of representative HAA and radical-addition pathways.~~Reaction with molecular O_2 typically governs its rapid oxidative evolution, while its reaction with •NO_2 can lead to the formation of more toxic and more strongly light-absorbing nitrated products. Therefore, to fully delineate the atmospheric transformation pathways and final products of 2,4-DNP, it is essential to systematically investigate the reaction mechanisms of IM3' with both O_2 and •NO_2.~~

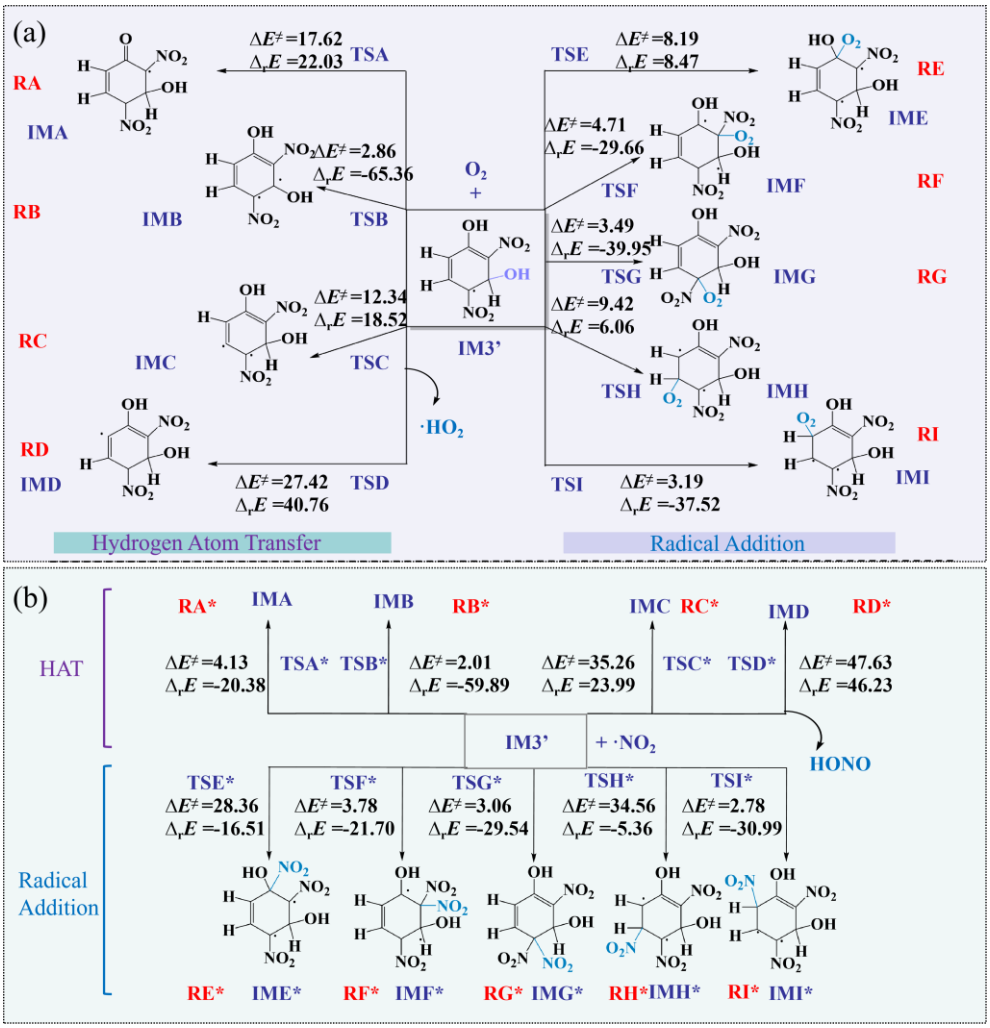


Figure 4 The subsequent reactivity mechanism of the key intermediate IM3' (unit: kcal mol^{-1}).

A systematic analysis was conducted for the reaction pathways of the intermediate IM3' with O_2 and •NO_2. For the reaction with O_2, as shown in Figure 4a, IM3' mainly evolves through two competing pathways, namely HAA and radical addition. The HAA pathway contains four distinct subchannels, among which the RB (hydrogen abstraction at C3) channel is the most favorable both thermodynamically and kinetically~~thermodynamics and kinetics~~. It is characterized by a remarkably low transition-state energy barrier of 2.86 kcal mol^{-1} and a highly exothermic reaction energy of –65.36 kcal mol^{-1}. In

this process, the O_2 molecule approaches the activated C3–H bond. The reaction is directed to the C3 position because this carbon is flanked by two strongly electron-withdrawing nitro groups at the adjacent C2 and C4 positions. This electronic effect substantially lowers the electron density and weakens the C3–H bond, making it the most favorable site for hydrogen abstraction. Key structural parameters in transition state TSB reveal a concerted mechanism: the distance between the attacking oxygen atom Oa of O_2 and the transferring hydrogen shortens significantly, while the breaking C3–H bond elongates accordingly, indicating synchronous bond breaking and bond forming. This synchronous bond-breaking and bond-forming process yields the phenoxy radical intermediate IMB and the hydroperoxyl radical ($•HO_2$). In contrast, the other HAA channels involving abstraction from the C5, C6, or hydroxyl positions have substantially higher calculated barriers and are therefore less favorable within the investigated reaction framework~~have much higher energy barriers and are therefore kinetically uncompetitive under realistic atmospheric conditions~~. In the competing radical addition pathway, the most favorable channel is RI, in which O_2 adds to the C4 position via the transition state TSI. This process has an energy barrier of 3.19 kcal mol^{-1} and is exothermic by –37.52 kcal mol^{-1}. Because this barrier is close to that of the optimal HAA channel RB, the HAA and radical addition pathways for the reaction of IM3' with O_2 are expected to compete directly at the molecular level.

The reaction of IM3' with $•NO_2$ similarly follows a competitive mechanism involving HAA and radical addition (Figure 4b). Within the HAA pathway, the RB* channel shows a clear advantage analogous to that observed in the O_2 system, with a

low energy barrier of 2.01 kcal mol^{-1} and a highly exothermic reaction energy of –59.89 kcal mol^{-1}. The mechanism of this process is highly consistent with that of the O_2-involved RB channel, in which the oxidant abstracts the hydrogen atom from the C3 position, yielding the identical phenoxy radical intermediate IMB, while producing HONO or $•HO_2$, respectively. In the radical addition pathway, the most feasible route is the RI* channel, with a barrier of 2.78 kcal mol^{-1} and a reaction energy of –30.99 kcal mol^{-1}. Similar to the O_2 addition pathway, $•NO_2$ preferentially adds to the C4 position, generating the nitro-substituted cyclohexadienyl radical intermediate IMI*. Comparison of the lowest energy barriers for the two pathways reveals that, within the investigated IM3'+ $•NO_2$ reaction system, the HAA pathway ~~is~~ has a ~~kinetically and~~ slightly lower calculated barrier ~~more favorable~~ than the radical--addition pathway~~path~~. Thus, HAA is the lower-barrier pathway among the $•NO_2$ reaction channels examined here, consistent with the corresponding barrier comparison for the O_2 reaction system.~~This establishes HAA as the dominant mechanism in the reaction of IM3' with $•NO_2$, consistent with the conclusion drawn for the O_2 system.~~ This corresponds to Level (ii) of $•NO_2$ involvement as distinguished in Section 3.1.2: the reaction of $•NO_2$ with a primary oxidation intermediate. ~~While O_2 dominates the overall fate of IM3' due to its concentration advantage (see below), the~~ The calculated low barrier for the $•NO_2$ + IM3' HAA pathway (2.01 kcal mol^{-1}) indicates that this indirect $•NO_2$ pathway is mechanistically feasible. However, its atmospheric contribution cannot be inferred

from the energy barrier alone and depends on competition with O_2 and other reactants~~suggests that nitration via this indirect route could be significant under elevated $\bullet NO_2$ conditions, such as in polluted urban plumes at night~~.

To illustrate this competition, effective pseudo-first-order ~~It should be emphasized that the competition between O_2 and $\bullet NO_2$ for IM3' must be evaluated based on effective~~ rates (k × [oxidant]) were estimated using representative atmospheric concentrations and literature-based rate coefficients~~rather than second-order rate constants alone~~. The atmospheric concentration of O_2 was taken as~~is~~ 5.4×10^{18} molecules cm^{-3} (0.21 atm). For the reaction of IM3' with O_2 via HAA (calculated barrier = 2.86 kcal mol^{-1}), ~~the barrier height indicates that the reaction is near the gas-kinetic limit, with~~ rate constants for analogous~~alkyl~~ radical + O_2 reactions are typically in the range of $10^{-12} \sim 10^{-11}$ cm^3 $molecule^{-1}$ s^{-1} (Miyoshi et al., 1990; Morgan et al., 1982). Using~~Taking~~ a conservative estimate of $k_{O2} \approx 10^{-12}$ cm^3 $molecule^{-1}$ s^{-1}, gives an ~~the~~ effective pseudo-first-order rate coefficient of~~is~~ $k'_{O2} \approx 10^{-12} \times 5.4 \times 10^{18} \approx 5.4 \times 10^6$ s^{-1}, corresponding to an illustrative reaction timescale of approximately 0.2 μs. This estimate is ~~a lifetime of 0.2 microseconds~~ consistent with the generally rapid reactions of organic ~~well-established behavior that alkyl~~ radicals ~~react~~ with O_2 ~~on timescales of 10 ~ 100 nanoseconds~~(Vereecken and Francisco, 2012; Calvert et al., 2015).

For the reaction of IM3' with $\bullet NO_2$ via HAA (barrier = 2.01 kcal mol^{-1}), assuming a representative nighttime $\bullet NO_2$ concentration of ~~even under the most favorable nighttime conditions with $[\bullet NO_2] \approx$~~ $10^{10} \sim 10^{11}$ molecules cm^{-3}~~,~~ and a literature-based rate coefficient of~~taking~~ $k_{NO2} \approx 10^{-11}$ cm^3 $molecule^{-1}$ s^{-1} ~~, the effective rate is~~gives k'_{NO2}

≈ 10^{-1} ~ 1 s^{-1}, corresponding to an illustrative reaction timescale of approximately ~~a lifetime of~~ 1 ~ 10 s~~econds~~. Under these assumptions, the effective O_2 reaction rate exceeds that of the investigated •NO_2 pathway by more than six orders of magnitude. Thus, although the low calculated barrier demonstrates the mechanistic feasibility of the indirect •NO_2 pathway, this illustrative effective-rate comparison suggests that reaction with O_2 would strongly outcompete the investigated •NO_2 pathway under the conditions considered here. Quantifying the atmospheric branching of IM3' would require reaction-specific rate coefficients and a more complete treatment of competing loss processes~~Thus, k'O_2 is more than 6 orders of magnitude faster than k'NO_2. The overwhelming concentration advantage of O_2 — more than 10^7 times that of •NO_2 — ensures that the reaction of IM3' with O_2 is the dominant atmospheric fate of this intermediate. This is fully consistent with the established behavior that addition of O_2 is essentially the sole atmospheric fate of organic radicals formed during the oxidation of organic compounds(Calvert et al., 2015)~~.

3.2. Molecular dynamics

Although the homogeneous oxidation mechanisms of 2,4-DNP in the gas and aqueous phases have been clarified, its heterogeneous interfacial behavior on aerosol particle surfaces remains to be elucidated. ~~As a representative model of atmospheric nanoparticles,~~ C60 provides a well-defined model system ~~offers an ideal system~~ for probing the non-covalent interactions between pollutants and particulate matter, owing to its well-defined carbon framework and surface curvature (Athar and Patnaik, 2022). The results obtained with this surrogate provide molecular-level insights into specific

interaction mechanisms, but should not be directly extrapolated to real atmospheric aerosols without considering the additional complexity of real particle surfaces. In this study, the IGM was employed to qualitatively and quantitatively analyze the weak interactions within the adsorption complexes (Lu and Chen, 2022), thereby revealing the interactions that govern the interfacial behavior at the molecular level.

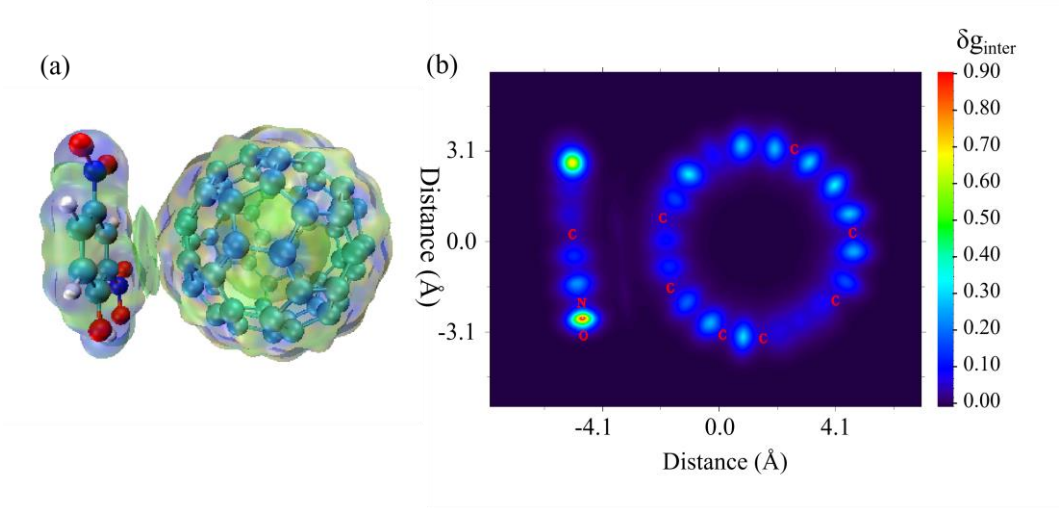


Figure 5 IGM analysis of intermolecular interactions in the 2,4-DNP-C60 aggregate. (a) three-dimensional (3D) IGM isosurface map. (b) two-dimensional (2D) IGM density map.

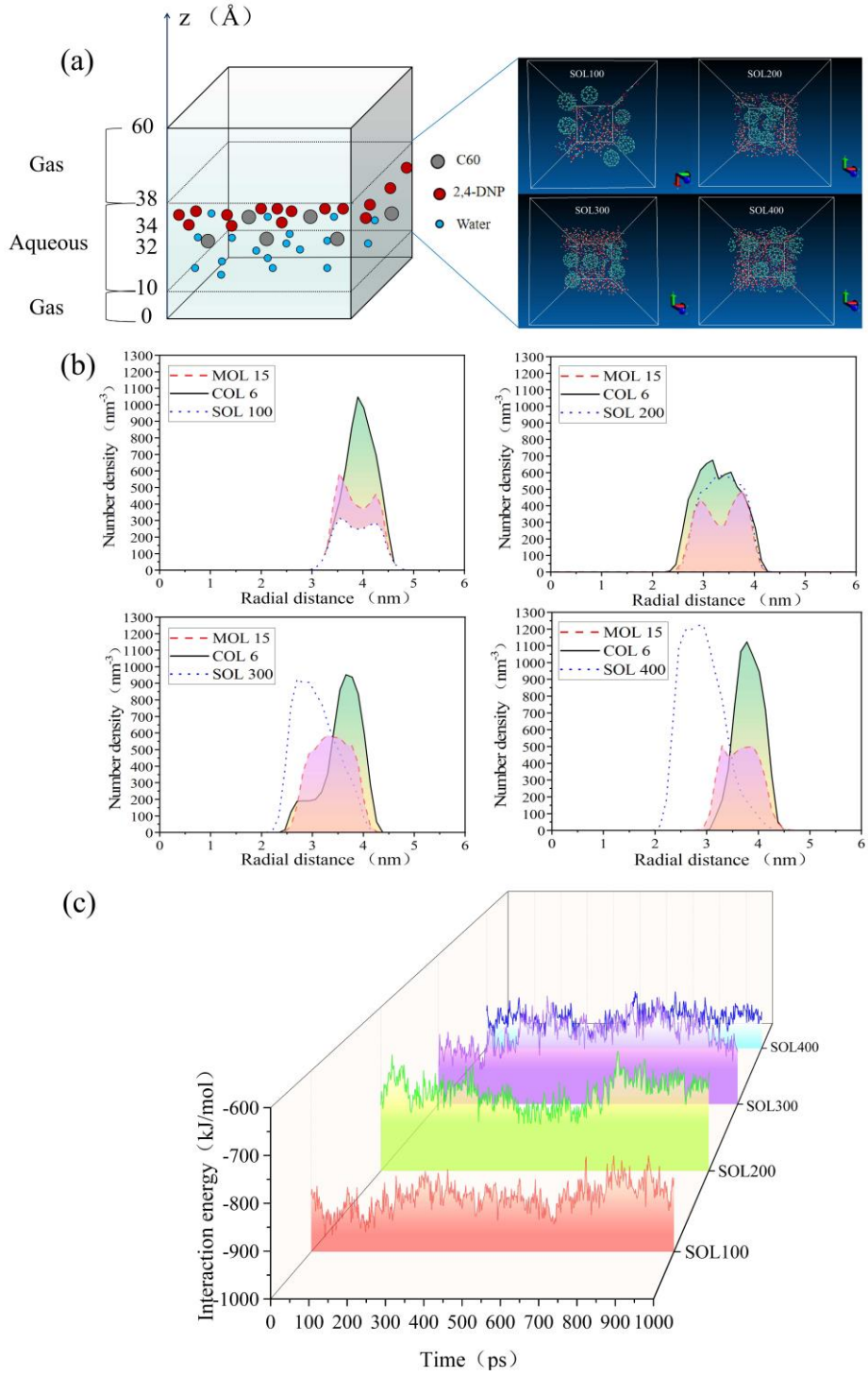
The intermolecular interactions within the 2,4-DNP-C60 aggregate were characterized utilizing the IGM by defining each monomer as an individual fragment. The intermolecular interaction pattern at the 2,4-DNP-C60 interface is elucidated jointly by the three-dimensional IGM isosurface map (Figure 5a) and the two-dimensional density map (Figure 5b), which exhibit excellent consistency. According to the principles of IGM analysis, the green and light-green isosurface regions, where sign($\lambda 2$) $\approx$ 0, correspond to van der Waals (vdW) interactions, indicative of diffuse and non-directional weak attractions. In contrast, the blue regions, characterized by sign($\lambda 2$) < 0, indicate

directional interactions such as hydrogen bonds or strong electrostatic attractions, which are associated with more localized electron-density distributions.

Specifically, the extensive green/light-green isosurface between the C60 cage and the benzene ring of 2,4-DNP corresponds closely to the continuous blue-to-light-blue signal band in the 2D density map ($\delta g_{inter} \approx 0.10–0.30$), confirming that vdW interactions, mainly dispersion and induction forces arising from the π-electron clouds of the benzene ring and fullerene surface, dominate the interfacial binding between 2,4-DNP and C60. Meanwhile, distinct blue regions are observed near the polar functional groups of 2,4-DNP, namely the nitro and hydroxyl moieties. These features manifest as localized yellow-green hotspots in the 2D density map ($\delta g_{inter} \approx 0.60–0.80$), indicating stronger polar interactions. These interactions can be attributed to specific directional forces, including a O–H···π hydrogen bond involving the hydrogen atom of the –OH group and the delocalized π-electron cloud of C60, as well as a dipole-π interaction between the oxygen atoms of the $–NO_2$ groups and the fullerene surface. These synergistic polar interactions enhance both the binding selectivity and the overall stability of the 2,4-DNP-C60 interface.

Further analysis indicates that the 2,4-DNP molecule preferentially adsorbs with its benzene ring approximately parallel to the C60 surface. In this configuration, the nonpolar benzene ring maximizes the dispersion interaction area by closely approaching the carbon cage via vdW forces, while the polar –OH and $–NO_2$ groups remain oriented outward. This arrangement not only avoids steric repulsion with the C60 sur-

face corresponding to strong steric hindrance, but also facilitates hydrogen-bond-network formation between the polar groups of neighboring 2,4-DNP molecules. In the 2D IGM cross-sectional map, this orientation is reflected by a clear spatial separation between the polar hotspots of the 2,4-DNP and the van der Waals signal band associated with C60, with the hotspot positions precisely corresponding to the atomic coordinates of the polar functional groups.



837

838 **Figure 6** (a) Molecular dynamics simulation framework construction (MOL: 2,4-DNP;

839 COL: C60; SOL: water). (b) z-axis number density profile of molecules (units: nm^{-3}).

840 (c) Hydration-dependent adsorption energies of 2,4-DNP on C60 (units: kJ mol^{-1}).

Building upon the fundamental interaction mechanisms revealed by IGM in the anhydrous system, molecular dynamics simulations were further carried out to investigate how hydration, as a key environmental factor, dynamically regulates the adsorption behavior of 2,4-DNP on C60 under atmospherically relevant conditions. Figure 6a illustrates the initial simulation setup, which consists of 15 molecules of 2,4-DNP and 6 molecules of C60 placed in a three-layer simulation box measuring 30 × 30 × 60 $Å^3$, with a gas-aqueous-gas sandwich structure. Different hydration levels were modeled by varying the number of water molecules from SOL100 to SOL400. The system then underwent energy minimization and molecular dynamics relaxation to obtain an equilibrated structure. In the aqueous phase, the distribution of 2,4-DNP and C60 gradually shifted toward the center of the water layer as the number of water molecules increased, indicating that the introduction of water significantly altered the spatial distribution pattern of the solutes.

The number-density distribution profiles along the z-axis in Figure 6b further reveal the influence of hydration on the axial distribution and aggregation behavior of the solute molecules. Combined with the strong intermolecular interactions revealed by IGM in the anhydrous system, it can be inferred that under low hydration conditions, 2,4-DNP and C60 tend to form compact aggregates because of their relatively strong mutual attraction. As the number of water molecules increases from SOL200 to SOL400, the density peak shifts toward larger radial distances (4.0–4.5 nm) and its height gradually rises. This indicates that water molecules disrupt the close aggregation

tendency between 2,4-DNP and C60 through competitive solvation, promoting the outward diffusion of solute molecules along the z-axis and thereby significantly enhancing the overall dispersity of the system.

Based on the temporal evolution of the interaction energies shown in Figure 6c, the dynamic regulatory role of hydration on intermolecular adsorption behavior can be further interpreted from an energetic perspective. In the low-hydration system SOL100, the interaction energy remains stable at approximately –850 kJ mol^{-1}. Its relatively large negative value is consistent with the compact aggregated state shown in Figure 6b, indicating strong direct adsorption between 2,4-DNP and C60 under these conditions. As the number of water molecules increases to SOL200, the absolute value of the interaction energy increases further, suggesting enhanced intermolecular attraction. This change may originate from moderate hydration, where water molecules may promote specific orientations and stabilize solute interactions through effects such as dielectric screening or indirect bridging (Lyu et al., 2025). However, when the hydration level further increases to SOL400, the absolute value of the interaction energy decreases, implying a significant weakening of intermolecular adsorption. This indicates that under high hydration conditions, water molecules suppress the direct interaction between 2,4-DNP and C60, thereby driving the system toward a more dispersed and stable solvated state. This non-monotonic energy trend, which first strengthens and then weakens, is consistent with the morphological evolution of solute distribution shown in Figure 6b, namely a transition from an initially aggregated state to a more dispersed

one. Together, these results reveal the complex regulatory role of hydration in interfacial adsorption behavior.

To assess statistical uncertainty arising from initial conditions, four independent replica simulations were performed for each hydration level by assigning distinct initial atomic velocities, thereby generating statistically independent trajectories in phase space. Error analysis demonstrates that the main conclusions regarding the adsorption configuration and distribution of 2,4-DNP at the gas-aqueous interface remain consistent across all replicas, underscoring the robustness and reproducibility of the results.

The MD simulations presented here are restricted~~limited~~ to molecular-scale adsorption behavior in the idealized C60/water/2,4-DNP system. The results provide insights into how hydration modulates specific non-covalent interactions, but they do not account for key aerosol properties that govern humidity-dependent behavior~~control humidity effects~~ in real atmospheric particles, ~~—~~including liquid water content, ionic strength, phase behavior, viscosity, and particle morphology. These properties ~~can~~ vary ~~substantially~~ with relative humidity, particle composition, and atmospheric conditions, thereby influencing particle ~~and~~ physical state and water uptake of aerosol particles~~they collectively determine the physical state and water uptake of aerosol particles~~. The simulations therefore represent a simplified model system. The MD results should be interpreted as molecular-scale insights into adsorption behavior rather than as direct predictions of atmospheric persistence or humidity-dependent partitioning. The present simulations do not quantitatively constrain atmospheric residence time, gas-particle partitioning, or long-range transport. These quantities require additional partitioning

calculations and atmospheric chemistry and transport modeling.~~Their absence in the current model means that the simulated hydration effects represent a simplified scenario that may not fully capture the complexity of real aerosol surfaces. Consequently, the MD results should be interpreted as molecular-scale insights into adsorption behavior under idealized conditions, rather than as direct predictions of atmospheric persistence or humidity-dependent partitioning. Quantitative assessments of atmospheric residence time, gas–particle partitioning, or long-range transport would require additional modeling that incorporates these aerosol properties and atmospheric transport processes, and are beyond the scope of the present study.~~

3.3 Predicted toxicity indicators ~~Ecotoxicity assessment~~

The reaction of ozone with aromatic rings follows a relatively well-defined mechanism and produces a comparatively clear product spectrum, making it a comparatively clear model for evaluating the directional impact of atmospheric oxidation on the toxicity of 2,4-DNP. By focusing on the O_3 pathway~~, one of the key atmospheric oxidants~~, this study ~~enables a precise analysis of the oxidation degradation pathways of 2,4-DNP and the toxicity of its products.~~provides a defined set of reactions for examining predicted changes in toxicity indicators along this specific transformation products. The conclusions drawn here may provide~~serve~~ a useful ~~toxicological~~ reference for future investigations of the more complex atmospheric oxidation networks involving radicals such as •OH and •NO_2. Accordingly, ~~based on~~ the key intermediates and final products (IM17, IM25, IM44, IM54, P1–P4) identified in Figure S2, ~~their mutagenic and devel-~~

~~opmental toxicity potentials~~ were predicted using the T.E.S.T. tool (Epa, 2020) to predict Ames mutagenicity and developmental toxicity indicators and to examine changes in predicted toxicity indicators ~~aiming to reveal the toxicity evolution pattern~~ along this specific oxidation process. A conceptual ~~mass fate~~ diagram integrating the investigated DFT reaction pathways~~DFT kinetics~~, MD ~~-~~derived interfacial adsorption behavior~~ad-sorption~~, and QSAR toxicity predictions is provided in Figure S3 to summarize the scope of the present computational framework~~illustrate the overall atmospheric transformation framework of 2,4-DNP~~. The framework considers gas-phase oxidation, bulk aqueous-phase oxidation, and interfacial adsorption behavior, with gas-aqueous partitioning influenced by Henry's law behavior and acid-base speciation. Oxidation pathways calculated by DFT generate key intermediates IM3' and IM17. These intermediates further transform into a series of products, and the Ames mutagenicity and developmental toxicity indicators of selected transformation products were evaluated using QSAR models~~of transformation products are evaluated via yield-weighted QSAR prediction~~.

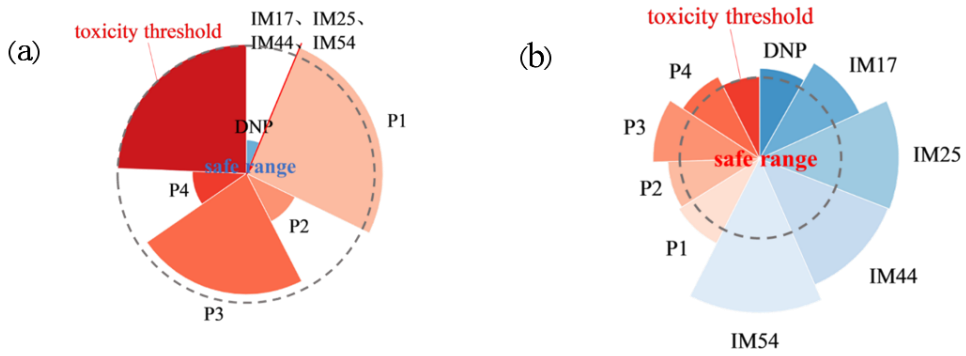


Figure 7 Toxicity prediction of 2,4-DNP and its transformation products. (a) Ames mutagenicity. (b) Developmental toxicity.

Differences in the predicted ~~The risk differences in~~ Ames mutagenicity and developmental toxicity indicators~~potential~~ between 2,4-DNP and the intermediates (IMs series) and final products (Ps series) generated from its reaction with ozone are intuitively illustrated in Figure 7. Regarding Ames mutagenicity in Figure 7a, the parent compound 2,4-DNP exhibits a predicted value of 0.13 that falls below the model classification ~~within the safety~~ threshold. The specific data are presented in Table S5. In contrast, the final products show higher predicted Ames mutagenicity indicators in the QSAR model. Notably, the predicted value for P1 (0.53) exceeds the model classification threshold. Within the QSAR framework, these results indicate that ozonolysis does not uniformly decrease the predicted Ames mutagenicity indicators of the modeled products.

~~its ozonolysis products display a marked divergence in mutagenic potential. Although primary intermediates (IM17, IM25, IM44, IM54) show no detectable mutagenicity, the final products generally demonstrate elevated mutagenic risk. Notably, the predicted value for product P1 (0.53) exceeds the toxicity threshold, placing it within the high-risk zone. This result clearly indicates that the ozonolysis does not necessarily reduce the mutagenicity of 2,4-DNP, instead, by generating more reactive intermediates and final products, it may significantly increase the overall genotoxic risk of the reaction system.~~

For developmental toxicity (Figure 7b), the parent compound has a predicted value of 0.55, whereas the modeled ozonolysis products generally show higher predicted values, with IM54 reaching 0.94. P2 and P4 have predicted values of 0.56, slightly higher

than that of the parent compound. The differences between the Ames mutagenicity and developmental toxicity predictions further illustrate that the two QSAR endpoints do not necessarily vary in parallel across the modeled transformation products. ~~In terms of developmental toxicity in Figure 7b, 2,4-DNP itself shows a baseline potential of 0.55, which is further exacerbated by ozonolysis. All derived products show higher developmental toxicity than the parent compound, with the risk reaching a maximum for IM54 (0.94). Notably, P2 and P4, despite their relatively low Ames mutagenicity (0.21), still exhibit a developmental toxicity potential of 0.56, which are higher than that of the parent compound. This reveals a decoupling between mutagenicity and developmental toxicity, suggesting that the oxidation process may generate novel hazardous specific developmental toxicity even when their mutagenic potential remains relatively low. Overall, the analysis indicates that the ozonolysis of 2,4-DNP does not constitute a harmless degradation pathway. On the contrary, it leads to the generation of more intermediate and final products with enhanced mutagenic and developmental toxicity.~~

Overall, the QSAR analysis predicts that some ozonolysis products exhibit higher predicted indicators of Ames mutagenicity and/or developmental toxicity than the parent 2,4-DNP. These compound-level predictions describe changes in modeled toxicity indicators and should not be interpreted as demonstrating increased environmental or health risk, which would additionally require information on product yields, environmental concentrations, exposure, and experimentally validated toxicity.

To further assess the reliability of the QSAR predictions, an independent cross-validation was performed using Toxtree (version 3.1.0) (Patlewicz et al., 2008). For

Ames mutagenicity, Toxtree's Benigni/Bossa rule-base was employed, which uses rule-based structural alerts that are algorithmically distinct from the statistical consensus method used in T.E.S.T (Benigni et al., 2007). The cross-validation results (Table S5) show consistent predictions for the majority of compounds, with deviations observed only for compounds with probability scores close to the classification threshold. For developmental toxicity, Toxtree does not provide a dedicated prediction model. Instead, we employed its Cramer decision tree to perform a toxicological concern threshold (TTC)-based classification. The Cramer decision tree classifies compounds into three classes based on their chemical structure: Class I (low toxicity concern), Class II (moderate toxicity concern), and Class III (high toxicity concern)(Cramer et al., 1976). Class III compounds are assigned the lowest TTC value (90 μg person^{-1} day^{-1}) (Munro et al., 1996), indicating the highest potential for adverse health effects, including developmental toxicity. As shown in Table S5, all 2,4-DNP and its ozonolysis products were classified as Cramer Class III, consistent with the T.E.S.T. predictions that all compounds exhibit developmental toxicity potential. This approach follows established practices in computational toxicology for the developmental toxicity screening of nitro-organic compounds (Yong-Di et al., 2022).

The toxicity predictions presented here are screening level assessments based on QSAR models. They are intended for hazard prioritization and hypothesis generation, not as definitive toxicological conclusions. Several factors limit their predictive reliability. First, QSAR model performance is constrained by the chemical space of training sets and the defined applicability domains. For structurally distinct species such as 2,4-

DNP and its various derivatives, the predicted confidence levels are lower because these models cannot fully elucidate specific toxicological modes of action. As highlighted by the Ames/QSAR International Challenge Projects, even the best performing models achieve a balanced accuracy of approximately 76.9 % at 100 % coverage (Uesawa, 2024). Second, categorical predictions with probability scores close to the classification threshold are inherently unstable, suggesting that the "not detected" Ames mutagenicity signals for intermediates such as IM17, IM25, IM44, and IM54 may reflect model limitations rather than a definitive absence of toxicity. Furthermore, these computational frameworks necessarily simplify complex biological endpoints such as developmental toxicity. While a quantitative weight of evidence (qWoE) approach has been shown to achieve accuracy comparable to experimental Ames tests (Tintó-Moliner and Martin, 2020), such approaches are beyond the scope of this screening level study. Overall, the findings should be interpreted as hypothesis-generating (Vom Eyser et al., 2013). Experimental validation ~~—~~through in vitro Ames tests and zebrafish embryo development toxicity assays would be valuable for evaluating the QSAR-predicted toxicity indicators of selected transformation products. ~~— is recommended for the high-priority compounds identified here.~~

4 Conclusions

This study systematically investigated selected chemical transformation pathways, molecular-scale interfacial behavior, and predicted toxicity changes ~~the chemical transformation mechanisms, multiphase interfacial behavior, and toxicity evolution~~ of 2,4-DNP ~~in the atmosphere~~ using an integrated computational framework combining DFT,

MD simulations, and QSAR models. ~~The main quantitative findings are:~~ Among the direct gas-phase reactions examined here, the calculated rate coefficient for the •OH pathway is higher than those for O_3 and $•NO_2$, while the aqueous-phase calculations indicate appreciable intrinsic reactivity toward O_3~~the atmospheric degradation of 2,4-DNP is dominated by the •OH pathway in the gas phase, while O_3 plays a significant role in the aqueous phase~~; the direct reaction of $•NO_2$ with the parent compound is kinetically unfavorable (gas-phase rate constant on the order of ~10^{-28} cm^3 $molecule^{-1}$ s^{-1}~~, more than 13 orders of magnitude lower than that of •OH~~), although reactions of $•NO_2$ with oxidation intermediates (barrier as low as 2.01 kcal mol^{-1}) and multiphase $•NO_2/O_3$ chemistry represent additional mechanistic pathways that warrant further investigation~~distinct pathways that may be environmentally relevant under certain conditions~~; solvation effects and the electron-withdrawing nitro groups substantially affect the calculated reaction kinetics~~suppress the initial reaction rates~~; within the investigated O_2 and $•NO_2$ reaction systems, HAA exhibits the lowest calculated barrier among the examined secondary pathways~~the key radical intermediate from •OH addition reacts with O_2 and $•NO_2$ predominantly via HAA~~; MD simulations show a non-monotonic hydration dependence of 2,4-DNP adsorption in the idealized C60/water system, with changes in hydration altering the molecular adsorption configurations and interaction strengths. These MD results represent molecular-scale behavior within the idealized model system and do not provide quantitative constraints on atmospheric residence time, gas-particle partitioning, or long-range transport~~MD simulations reveal that the adsorption behavior of 2,4-DNP on the idealized C60 aerosol surogate is regulated non-~~

~~monotonically by the degree of interfacial hydration, with enhanced solute-particle interactions under low-hydration conditions and weakened adsorption under high-hydration conditions.; and~~ QSAR predictions indicate that certain ozonolysis products exhibit higher predicted~~elevated~~ Ames mutagenicity and developmental toxicity ~~indicators relative to~~than the parent compound. ~~Compared to previous studies that focused on gas-phase photolysis and assumed oxidative detoxification, our work quantifies the cumulative electron-withdrawing effect of two nitro groups (rate constant three orders lower than mononitrocatechol) and predicts that ozonolysis products may exhibit increased toxicity indicators, challenging conventional assumptions that oxidative degradation necessarily leads to detoxification.~~ These results represent compound-level, screening-level predictions and do not establish increased environmental risk, which would require information on product yields, exposure, and experimentally validated toxicity. While the quantitative conclusions apply specifically to 2,4-DNP, the mechanistic relationships examined here among~~qualitative framework established here linking~~ substituent electronic effects, ~~to~~ reaction kinetics, interfacial behavior, and predicted toxicity indicators ~~—~~may ~~serve as a reference for understanding related nitroaromatic systems.~~ provide a basis for future investigations of related nitroaromatic compounds.

Several limitations should be noted. ~~:~~ The~~the~~ aerosol surrogate (C60), while useful for isolating specific non-covalent interactions, does not capture the full chemical complexity of real atmospheric particles, including ~~—particularly the presence of~~ oxygen-containing functional groups, surface defects, heteroatoms, and transition metals that

may influence reactivity and product formation.~~–~~ Consequently, the present model may emphasize π-π interactions while underrepresenting polar and chemically heterogeneous surface interactions~~As a result, the C60 model may overestimate the contribution of π-π interactions and underestimate the role of polar interactions~~. The present 1 ns MD simulations are limited in their ability to capture slower dynamical processes, particularly those occurring on more complex aerosol surfaces; longer simulations and more advanced force-fields treatments would therefore be valuable in future studies~~The 1 ns MD timescale is sufficient for the rigid C60/small molecule system studied here, but longer simulations and polarizable force fields may be needed to capture slower dynamical processes on more complex surfaces~~. The QSAR toxicity predictions are screening-level estimates requiring experimental validation. Moreover, quantitative determination of the relative contributions of the investigated pathways to the atmospheric loss of 2,4-DNP would require atmospheric chemistry modeling that incorporates ~~A full diurnal box model simulation incorporating~~ temporally resolved oxidant concentrations, gas-particle and gas-aqueous partitioning, aerosol liquid water content, and additional loss processes~~Henry's law partitioning, and aerosol liquid water content would be needed to fully quantify the atmospheric importance of each pathway under realistic conditions~~. Additionally, downstream multiphase aging processes such as oligomerization or metal-catalyzed reactions, which may influence the fate of phenolic compounds in real atmospheric particles, were not addressed in this study and would require complementary experimental and modeling approaches.

–Future work should therefore focus on experimental validation of the calculated reaction kinetics and QSAR predictions, more realistic representations of carbonaceous aerosol surfaces, and atmospheric chemistry modeling that explicitly incorporates phase partitioning and relevant loss processes. Within these limitations, the present results provide molecular-level mechanistic insight that can guide future experimental and modeling studies of nitrophenol multiphase chemistry.~~Future complementary simulations using more realistic carbon models, such as amorphous carbon clusters or graphene with functional groups, would be valuable to validate the trends identified here.~~

~~Based on these findings, we recommend the following directions for future research: (i) Experimental validation of predicted kinetics: Advanced kinetic techniques such as laser-induced fluorescence or cavity ring-down spectroscopy should be employed to measure the rate constants for the reactions of 2,4-DNP with O3 and •OH, providing direct experimental confirmation of the theoretical trends. (ii) In vitro toxicity testing: The high-priority ozonolysis products identified in this study (IM54, P1, and P2) should be subjected to Ames mutagenicity assays and zebrafish embryo developmental toxicity tests to validate the QSAR predictions. (iii) Refined interfacial models: Complementary MD simulations using more realistic carbonaceous models, such as functionalized graphene or amorphous carbon clusters, would help assess the influence of surface functional groups and defects on the adsorption behavior of 2,4-DNP. (iv) Diurnal box model simulations: Full diurnal chemical box models incorporating temporally resolved oxidant concentrations, Henry's law partitioning, and aerosol liquid water content are needed to fully quantify the atmospheric importance of each oxidation~~

~~pathway under different pollution regimes. Despite these caveats, the mechanistic insights into the molecular-level reactivity and interfacial behavior of 2,4-DNP provide a foundation for future experimental and modeling studies on the multiphase fate of nitrophenolic compounds.~~

Data availability

The data supporting this article have been included as part of the supplementary information or are available upon request.

Author contributions

Chenlei Wang conceptualized the study, curated the data, validated the results, and wrote the original draft. Ran Li and Jiaxing Sun conceptualized the study and curated the data. Zihan Zhang curated the data. Nan Zhao developed the software and validated the results. Zuju Ma developed the software, performed the visualization, and carried out the investigation. Maoxia He developed the methodology, performed the visualization, and carried out the investigation. Leilei Liu reviewed and edited the manuscript and acquired the funding. Jianfei Sun curated the data, reviewed and edited the manuscript, acquired the funding, supervised the project, and administered the project.

Competing interests

The authors declare that they have no conflict of interest.

Acknowledgements

This work was financially supported by Shandong Provincial Natural Science Foundation ZR2024MB037, and Natural Science Foundation of Yantai 2024JCYJ065.

References

Al-Abadleh, H. A., Motaghedi, F., Mohammed, W., Rana, M. S., Malek, K. A., Rastogi, D., Asa-Awuku, A. A., and Guzman, M. I.: Reactivity of aminophenols in forming nitrogen-containing brown carbon from iron-catalyzed reactions, Commun Chem, 5, 112, 10.1038/s42004-022-00732-1, 2022.

Albinet, A., Minero, C., and Vione, D.: Phototransformation processes of 2,4-dinitrophenol, relevant to atmospheric water droplets, Chemosphere, 80, 753-758, 10.1016/j.chemosphere.2010.05.016, 2010.

Andreae, M. O. and Gelencsér, A.: Black carbon or brown carbon? The nature of light-absorbing carbonaceous aerosols, Atmos. Chem. Phys., 6, 3131-3148, 10.5194/acp-6-3131-2006, 2006.

Athar, M. and Patnaik, A.: Through-Bond-Driven Through-Space Interactions in a Fullerene C60 Noncovalent Dyad: An Unusual Strong Binding between Spherical and Planar π Electron Clouds and Culmination of Dyadic Fractals, Journal of Physical Chemistry A, 126, 3629-3641, 10.1021/acs.jpca.1c10828, 2022.

Atkinson, R., Tuazon, E. C., Wallington, T. J., Aschmann, S. M., Arey, J., Winer, A. M., and Pitts, J. N.: Atmospheric chemistry of aniline, N, N-dimethylaniline, pyridine, 1,3,5-triazine, and nitrobenzene, Environmental Science & Technology, 21, 64-72, 10.1021/es00155a007, 1987.

Bejan, I., Barnes, I., Olariu, R., Zhou, S., Wiesen, P., and Benter, T.: Investigations on the gas-phase photolysis and OH radical kinetics of methyl-2-nitrophenols, Physical Chemistry Chemical Physics, 9, 5686-5692, 10.1039/b709464g, 2007.

Benfenati, E., Benigni, R., DeMarini, D. M., Helma, C., Kirkland, D., Martin, T. M., Mazzatorta, P., Ouédraogo-Arras, G., Richard, A. M., Schilter, B., Schoonen, W., Snyder, R., and Yang, C.: Predictive Models for Carcinogenicity and Mutagenicity: Frameworks, State-of-the-Art, and Perspectives, Journal of Environmental Science and Health Part C-Environmental Carcinogenesis & Ecotoxicology Reviews, 27, 57-90, 10.1080/10590500902885593, 2009.

Benigni, R., Bossa, C., Netzeva, T., Rodomonte, A., and Tsakovska, I.: Mechanistic QSAR of aromatic amines: new models for discriminating between homocyclic muta-

gens and nonmutagens, and validation of models for carcinogens, Environ Mol Mutagen, 48, 754-771, 10.1002/em.20355, 2007.

Calvert, J. G., Orlando, J. J., Stockwell, W. R., and Wallington, T. J.: The Mechanisms of Reactions Influencing Atmospheric Ozone, Oxford University Press, 10.1093/oso/9780190233020.001.0001, 2015.

Canneaux, S., Bohr, F., and Henon, E.: KiSThelP: A Program to Predict Thermodynamic Properties and Rate Constants from Quantum Chemistry Results, Journal of Computational Chemistry, 35, 82-93, 10.1002/jcc.23470, 2014.

Cassano, A., Manganaro, A., Martin, T., Young, D., Piclin, N., Pintore, M., Bigoni, D., and Benfenati, E.: CAESAR models for developmental toxicity, Chemistry Central Journal, 4, 10.1186/1752-153x-4-s1-s4, 2010.

Chapleski, R. C., Zhang, Y. F., Troya, D., and Morris, J. R.: Heterogeneous chemistry and reaction dynamics of the atmospheric oxidants, O_3, NO_3, and OH, on organic surfaces, Chemical Society Reviews, 45, 3731-3746, 10.1039/c5cs00375j, 2016.

Cornelissen, G., Gustafsson, O., Bucheli, T. D., Jonker, M. T. O., Koelmans, A. A., and M van Noort, P. C.: Extensive sorption of organic compounds to black carbon, coal, and kerogen in sediments and soils: mechanisms and consequences for distribution, bioaccumulation, and biodegradation, Environmental Science and Technology, 39, 10.1021/es050191b, 2005.

Cramer, G. M., Ford, R. A., and Hall, R. L.: Estimation of toxic hazard—A decision tree approach, Food and Cosmetics Toxicology, 16, 255-276, https://doi.org/10.1016/S0015-6264(76)80522-6, 1976.

Decesari, S., Kovarich, S., Pavan, M., Bassan, A., Ciacci, A., and Topping, D.: Evaluating the mutagenic potential of aerosol organic compounds using informatics-based screening, Atmos. Chem. Phys., 18, 2329-2340, 10.5194/acp-18-2329-2018, 2018.

Delaria, E. R. and Cohen, R. C.: Measurements of Atmosphere-Biosphere Exchange of Oxidized Nitrogen and Implications for the Chemistry of Atmospheric NO_x, Accounts of Chemical Research, 56, 1720-1730, 10.1021/acs.accounts.3c00090, 2023.

EPA, U. S.: User's Guide for T.E.S.T. (version 5.1) (Toxicity Estimation Software Tool):

A Program to Estimate Toxicity from Molecular Structure., U.S. Environmental Protection Agency, 2020.

Fan, W. L., Chen, T., Zhu, Z. L., Zhang, H., Qiu, Y. L., and Yin, D. Q.: A review of secondary organic aerosols formation focusing on organosulfates and organic nitrates, Journal of Hazardous Materials, 430, 10.1016/j.jhazmat.2022.128406, 2022.

Frisch, M. J., Trucks, G. W., Schlegel, H. B., Scuseria, G. E., Robb, M. A., Cheeseman, J. R., Scalmani, G., Barone, V., Petersson, G. A., Nakatsuji, H., Li, X., Caricato, M., Marenich, A. V., Bloino, J., Janesko, B. G., Gomperts, R., Mennucci, B., Hratchian, H. P., Ortiz, J. V., Izmaylov, A. F., Sonnenberg, J. L., Williams, Ding, F., Lipparini, F., Egidi, F., Goings, J., Peng, B., Petrone, A., Henderson, T., Ranasinghe, D., Zakrzewski, V. G., Gao, J., Rega, N., Zheng, G., Liang, W., Hada, M., Ehara, M., Toyota, K., Fukuda, R., Hasegawa, J., Ishida, M., Nakajima, T., Honda, Y., Kitao, O., Nakai, H., Vreven, T., Throssell, K., Montgomery Jr., J. A., Peralta, J. E., Ogliaro, F., Bearpark, M. J., Heyd, J. J., Brothers, E. N., Kudin, K. N., Staroverov, V. N., Keith, T. A., Kobayashi, R., Normand, J., Raghavachari, K., Rendell, A. P., Burant, J. C., Iyengar, S. S., Tomasi, J., Cossi, M., Millam, J. M., Klene, M., Adamo, C., Cammi, R., Ochterski, J. W., Martin, R. L., Morokuma, K., Farkas, O., Foresman, J. B., and Fox, D. J.: Gaussian 16 Rev. C.01, 2016.

Geyer, A., Bächmann, K., Hofzumahaus, A., Holland, F., Stefan, Konrad, Klüpfel, T., Pätz, H. W., Perner, D., Mihelcic, D., Schäfer, H. J., Volz-Thomas, A., and Platt, U.: Nighttime formation of peroxy and hydroxyl radicals during the BERLIOZ campaign: Observations and modeling studies, Journal of Geophysical Research, 108, 8249, 2003.

Guzman, M. I., Pillar-Little, E. A., and Eugene, A. J.: Interfacial Oxidative Oligomerization of Catechol, ACS Omega, 7, 36009-36016, 10.1021/acsomega.2c05290, 2022.

Hems, R. F. and Abbatt, J. P. D.: Aqueous Phase Photo-oxidation of Brown Carbon Nitrophenols: Reaction Kinetics, Mechanism, and Evolution of Light Absorption, ACS Earth and Space Chemistry, 2, 225-234, 10.1021/acsearthspacechem.7b00123, 2018.

Humphrey, W., Dalke, A., and Schulten, K.: VMD: Visual molecular dynamics, Journal of Molecular Graphics, 14, 33-38, https://doi.org/10.1016/0263-7855(96)00018-5, 1996.

Khan, M. A. H., Hoque, M. M. N., Alam, S. S., Ashfold, M. J., Nickless, G., and Shallcross, D. E.: Estimation and comparison of night-time OH levels in the UK urban atmosphere using two different analysis methods, Journal of Environmental Sciences, 23, 60-64, https://doi.org/10.1016/S1001-0742(10)60373-7, 2011.

Kroll, J. H. and Seinfeld, J. H.: Chemistry of secondary organic aerosol: Formation and evolution of low-volatility organics in the atmosphere, Atmospheric Environment, 42, 3593-3624, 10.1016/j.atmosenv.2008.01.003, 2008.

Kromann, J. C., Steinmann, C., and Jensen, J. H.: Improving solvation energy predictions using the SMD solvation method and semiempirical electronic structure methods, Journal of Chemical Physics, 149, 10.1063/1.5047273, 2018.

Lefebvre, C., Rubez, G., Khartabil, H., Boisson, J. C., Contreras-García, J., and Hénon, E.: Accurately extracting the signature of intermolecular interactions present in the NCI plot of the reduced density gradient versus electron density, Physical Chemistry Chemical Physics, 19, 17928-17936, 10.1039/c7cp02110k, 2017.

Li, J., Han, Z. W., Sun, Y. L., Li, J. W., and Liang, L.: Chemical formation pathways of secondary organic aerosols in the Beijing-Tianjin-Hebei region in wintertime, Atmospheric Environment, 244, 10.1016/j.atmosenv.2020.117996, 2021.

Li, J., Han, Z. W., Wu, J., Tao, J., Li, J. W., Sun, Y. L., Liang, L., Liang, M. J., and Wang, Q. G.: Secondary organic aerosol formation and source contributions over east China in summertime, Environmental Pollution, 306, 10.1016/j.envpol.2022.119383, 2022a.

Li, M., Wang, X. F., Lu, C. Y., Li, R., Zhang, J., Dong, S. W., Yang, L. X., Xue, L. K., Chen, J. M., and Wang, W. X.: Nitrated phenols and the phenolic precursors in the atmosphere in urban Jinan, China, Science of the Total Environment, 714, 10.1016/j.scitotenv.2020.136760, 2020.

Li, M., Wang, X. F., Zhao, Y. N., Du, P., Li, H. Y., Li, J. R., Shen, H. Q., Liu, Z. Y., Jiang, Y. R., Chen, J., Bi, Y. J., Zhao, Y., Xue, L. K., Wang, Y., Chen, J. M., and Wang, W. X.: Atmospheric Nitrated Phenolic Compounds in Particle, Gaseous, and Aqueous Phases During Cloud Events at a Mountain Site in North China: Distribution Characteristics and Aqueous-Phase Formation, Journal of Geophysical Research-Atmospheres, 127, 10.1029/2022jd037130, 2022b.

Li, P. Y., Feng, L., Li, G. Y., and Bai, F. Q.: Effects of Electron Donating Ability of Substituents and Molecular Conjugation on the Electronic Structures of Organic Radicals, Chemical Research in Chinese Universities, 39, 202-207, 10.1007/s40242-023-2364-2, 2023.

Lindorff-Larsen, K., Piana, S., Palmo, K., Maragakis, P., Klepeis, J. L., Dror, R. O., and Shaw, D. E.: Improved side-chain torsion potentials for the Amber ff99SB protein force field, Proteins, 78, 1950-1958, 10.1002/prot.22711, 2010.

Liu, Z. Y. and Lu, T.: Theoretical Insight into Complexation Between Cyclocarbons and C60 Fullerene, Chemistry-a European Journal, 30, 10.1002/chem.202402227, 2024.

Lu, T., TST calculator, http://sobereva.com/310 (accessed 12 11, 2025).

Lu, T., Sobtop, Version [1.0], http://sobereva.com/soft/Sobtop (accessed on 17 01 2026).

Lu, T. and Chen, F. W.: Multiwfn: A multifunctional wavefunction analyzer, Journal of Computational Chemistry, 33, 580-592, 10.1002/jcc.22885, 2012.

Lu, T. and Chen, Q. X.: Independent gradient model based on Hirshfeld partition: A new method for visual study of interactions in chemical systems, Journal of Computational Chemistry, 43, 539-555, 10.1002/jcc.26812, 2022.

Lüttke, J. and Levsen, K.: Phase partitioning of phenol and nitrophenols in clouds, Atmospheric Environment, 31, 2649-2655, https://doi.org/10.1016/S1352-2310(96)00228-2, 1997.

Lyu, Y., Xu, H., Yuan, H. X., Cui, Y. L., Zhang, C. Z., and Meng, Q. T.: Intermolecular interaction mechanisms between dinitrophenol and water: a molecular dynamics and DFT study, European Physical Journal Plus, 140, 10.1140/epjp/s13360-025-06478-8, 2025.

Maeda, S., Harabuchi, Y., Ono, Y., Taketsugu, T., and Morokuma, K.: Intrinsic Reaction Coordinate: Calculation, Bifurcation, and Automated Search, International Journal of Quantum Chemistry, 115, 258-269, 10.1002/qua.24757, 2015.

Mahilang, M., Deb, M. K., and Pervez, S.: Biogenic secondary organic aerosols: A review on formation mechanism, analytical challenges and environmental impacts, Chemosphere, 262, 10.1016/j.chemosphere.2020.127771, 2021.

Mayer, J. M.: Understanding hydrogen atom transfer: from bond strengths to Marcus

theory, Accounts of chemical research, 44, 36-46, 10.1021/ar100093z, 2011.

McNeill, V. F.: Atmospheric Aerosols: Clouds, Chemistry, and Climate, Annual Review of Chemical and Biomolecular Engineering, 8, 10.1146/annurev-chembioeng-060816-101538, 2017.

Miyoshi, A., Matsui, H., and Washida, N.: Rates of reaction of hydroxyalkyl radicals with molecular oxygen, The Journal of Physical Chemistry, 94, 3016-3019, 1990.

Morgan, C. A., Pilling, M. J., Tulloch, J. M., Ruiz, R. P., and Bayes, K. D.: Direct determination of the equilibrium constant and thermodynamic parameters for the reaction allyl radical + oxygen ⇌ allylperoxy radical, ChemInform, 13, 1982.

Munro, I. C., Ford, R. A., Kennepohl, E., and Sprenger, J. G.: Correlation of structural class with no-observed-effect levels: A proposal for establishing a threshold of concern, Food and Chemical Toxicology, 34, 829-867, https://doi.org/10.1016/S0278-6915(96)00049-X, 1996.

Nagy, P. R.: State-of-the-art local correlation methods enable affordable gold standard quantum chemistry for up to hundreds of atoms, Chem Sci, 15, 14556-14584, 10.1039/d4sc04755a, 2024.

Ng, N. L., Brown, S. S., Archibald, A. T., Atlas, E., Cohen, R. C., Crowley, J. N., Day, D. A., Donahue, N. M., Fry, J. L., Fuchs, H., Griffin, R. J., Guzman, M. I., Herrmann, H., Hodzic, A., Iinuma, Y., Jimenez, J. L., Kiendler-Scharr, A., Lee, B. H., Luecken, D. J., Mao, J., McLaren, R., Mutzel, A., Osthoff, H. D., Ouyang, B., Picquet-Varrault, B., Platt, U., Pye, H. O. T., Rudich, Y., Schwantes, R. H., Shiraiwa, M., Stutz, J., Thornton, J. A., Tilgner, A., Williams, B. J., and Zaveri, R. A.: Nitrate radicals and biogenic volatile organic compounds: oxidation, mechanisms, and organic aerosol, Atmospheric Chemistry & Physics, 17, 2103-2162, 10.5194/acp-17-2103-2017, 2017.

Patlewicz, G., Jeliazkova, N., Safford, R. J., Worth, A. P., and Aleksiev, B.: An evaluation of the implementation of the Cramer classification scheme in the Toxtree software, SAR and QSAR in environmental research, 19, 495-524, 10.1080/10629360802083871, 2008.

Perumpully, S. J. and Gautam, S.: Impact of aerosols on atmospheric processes and

climate variability: A synthesis of recent research findings, Geosystems and Geoenvironment, 4, 100317, https://doi.org/10.1016/j.geogeo.2024.100317, 2025.

Pillar-Little, E. A. and Guzman, M. I.: Oxidation of Substituted Catechols at the Air–Water Interface: Production of Carboxylic Acids, Quinones, and Polyphenols, Environmental Science & Technology, 51, 4951-4959, 10.1021/acs.est.7b00232, 2017.

Pillar-Little, E. A. and Guzman, M. I.: An Overview of Dynamic Heterogeneous Oxidations in the Troposphere, Environments, 5, 104, 2018.

Pillar-Little, E. A., Camm, R. C., and Guzman, M. I.: Catechol oxidation by ozone and hydroxyl radicals at the air-water interface, Environ Sci Technol, 48, 14352-14360, 10.1021/es504094x, 2014.

Pillar, E. A., Camm, R. C., and Guzman, M. I.: Catechol Oxidation by Ozone and Hydroxyl Radicals at the Air-Water Interface, Environmental Science & Technology, 48, 14352-14360, 10.1021/es504094x, 2014.

Pillar, E. A., Zhou, R., and Guzman, M. I.: Heterogeneous Oxidation of Catechol, Journal of Physical Chemistry A, 119, 10349-10359, 10.1021/acs.jpca.5b07914, 2015.

Pino-Rios, R., Inostroza, D., Cárdenas-Jirón, G., and Tiznado, W.: Orbital-Weighted Dual Descriptor for the Study of Local Reactivity of Systems with (Quasi-) Degenerate States, Journal of Physical Chemistry A, 123, 10556-10562, 10.1021/acs.jpca.9b07516, 2019.

Poster, D., Nguyen, T., Brown, R., and Ball, W.: Evidence for a pore-filling mechanism in the adsorption of aromatic hydrocarbons to a natural wood char, https://doi.org/10.1021/es0617845, 2007.

Qin, M., Xie, P., Su, H., Gu, J., Peng, F., Li, S., Zeng, L., Liu, J., Liu, W., and Zhang, Y.: An observational study of the HONO–NO_2 coupling at an urban site in Guangzhou City, South China, Atmospheric Environment, 43, 5731-5742, https://doi.org/10.1016/j.atmosenv.2009.08.017, 2009.

Rana, M. S. and Guzman, M. I.: Oxidation of Phenolic Aldehydes by Ozone and Hydroxyl Radicals at the Air–Water Interface, The Journal of Physical Chemistry A, 124, 8822-8833, 10.1021/acs.jpca.0c05944, 2020.

Rana, M. S. and Guzman, M. I.: Oxidation of Phenolic Aldehydes by Ozone and Hydroxyl Radicals at the Air-Solid Interface, ACS Earth Space Chem, 6, 2900-2909, 10.1021/acsearthspacechem.2c00206, 2022a.

Rana, M. S. and Guzman, M. I.: Oxidation of Catechols at the Air-Water Interface by Nitrate Radicals, Environ Sci Technol, 56, 15437-15448, 10.1021/acs.est.2c05640, 2022b.

Rana, M. S. and Guzman, M. I.: Mechanistic Insights into Heterogeneous Oxidation: Product-Resolved Analysis of Phenolic Aldehyde Films, ACS Physical Chemistry Au, 2026a.

Rana, M. S. and Guzman, M. I.: Heterogeneous Nitrate Radical Oxidation of Catechol Produces Nitrocatechols, Oligomers, and Brown Carbon, ACS Earth & Space Chemistry, 10, 2159 - 2170, 2026b.

Rana, M. S., Bradley, S. T., and Guzman, M. I.: Conversion of Catechol to 4-Nitrocatechol in Aqueous Microdroplets Exposed to O_3 and NO_2, ACS ES&T Air, 1, 80-91, 10.1021/acsestair.3c00001, 2023.

Salvador, C. M. G., Tang, R. Z., Priestley, M., Li, L. J., Tsiligiannis, E., Le Breton, M., Zhu, W. F., Zeng, L. M., Wang, H., Yu, Y., Hu, M., Guo, S., and Hallquist, M.: Ambient nitro-aromatic compounds - biomass burning versus secondary formation in rural China, Atmospheric Chemistry and Physics, 21, 1389-1406, 10.5194/acp-21-1389-2021, 2021.

Schwarzenbach, R. P., Stierli, R., Folsom, B. R., and Zeyer, J.: Compound properties relevant for assessing the environmental partitioning of nitrophenols, 22:1, 10.1021/es00166a009

Journal Name: Environ. Sci. Technol.; (United States) Journal Volume: 22:1, 1988.

Shenghur, A., Weber, K. H., Nguyen, N. D., Sontising, W., and Tao, F. M.: Theoretical Study of the Hydrogen Abstraction of Substituted Phenols by Nitrogen Dioxide as a Source of HONO, Journal of Physical Chemistry A, 118, 11002-11014, 10.1021/jp508516c, 2014.

Shi, K., Mei, X. L., Chen, C. R., and Liu, C. Q.: Impact of atmospheric O_3 and NO_2 on the secondary sulfates in real atmosphere, Journal of Environmental Sciences, 150, 277-287, 10.1016/j.jes.2024.02.019, 2025.

Shirts, M. R., Pitera, J. W., Swope, W. C., and Pande, V. S.: Extremely precise free energy calculations of amino acid side chain analogs: Comparison of common molecular mechanics force fields for proteins, Journal of Chemical Physics, 119, 5740-5761, 10.1063/1.1587119, 2003.

Shukla, S. S., Dorris, K. L., and Chikkaveeraiah, B. V.: Photocatalytic degradation of 2,4-dinitrophenol, Journal of Hazardous Materials, 164, 310-314, 10.1016/j.jhazmat.2008.08.047, 2009.

Spiegel, M., Semidalas, E., Martin, J. M. L., Bentley, M. R., and Stanton, J. F.: Post-CCSD(T) corrections to bond distances and vibrational frequencies: the power of Λ, Molecular Physics, 122, 10.1080/00268976.2023.2252114, 2024.

Steiner, T.: The Hydrogen Bond in the Solid State, Angewandte Chemie International Edition, 41, 48-76, https://doi.org/10.1002/1521-3773(20020104)41:1<48:AID-ANIE48>3.0.CO;2-U, 2002.

Sun, J., Mu, Q., Kimura, H., Murugadoss, V., He, M., Du, W., and Hou, C.: Oxidative degradation of phenols and substituted phenols in the water and atmosphere: a review, Advanced Composites and Hybrid Materials, 5, 627-640, 2022.

Sushko, I., Novotarskyi, S., Körner, R., Pandey, A. K., Cherkasov, A., Li, J., Gramatica, P., Hansen, K., Schroeter, T., Müller, K. R., Xi, L., Liu, H., Yao, X., Öberg, T., Hormozdiari, F., Dao, P., Sahinalp, C., Todeschini, R., Polishchuk, P., Artemenko, A., Kuz'min, V., Martin, T. M., Young, D. M., Fourches, D., Muratov, E., Tropsha, A., Baskin, I., Horvath, D., Marcou, G., Muller, C., Varnek, A., Prokopenko, V. V., and Tetko, I. V.: Applicability domains for classification problems: Benchmarking of distance to models for Ames mutagenicity set, J Chem Inf Model, 50, 2094-2111, 10.1021/ci100253r, 2010.

Szatylowicz, H., Jezuita, A., Ejsmont, K., and Krygowski, T. M.: Substituent Effect on the σ- and π-Electron Structure of the Nitro Group and the Ring in Meta- and Para-Substituted Nitrobenzenes, Journal of Physical Chemistry A, 121, 5196-5203, 10.1021/acs.jpca.7b03418, 2017.

Tam, J. Y. C., Lorsbach, T., Schmidt, S., and Wicker, J. S.: Holistic evaluation of bio-

degradation pathway prediction: assessing multi-step reactions and intermediate products, Journal of Cheminformatics, 13, 63, 10.1186/s13321-021-00543-x, 2021.

Tintó-Moliner, A. and Martin, M.: Quantitative weight of evidence method for combining predictions of quantitative structure-activity relationship models, SAR and QSAR in Environmental Research, 31, 261-279, 10.1080/1062936X.2020.1725116, 2020.

Tiwari, J., Tarale, P., Sivanesan, S., and Bafana, A.: Environmental persistence, hazard, and mitigation challenges of nitroaromatic compounds, Environmental Science and Pollution Research, 26, 28650-28667, 10.1007/s11356-019-06043-8, 2019.

Tomas, A., Olariu, R. I., Barnes, I., and Becker, K. H.: Kinetics of the reaction of O_3 with selected benzenediols, International Journal of Chemical Kinetics, 35, 223-230, https://doi.org/10.1002/kin.10121, 2003.

Tuñón, I. and Williams, I. H.: Chapter Two - The transition state and cognate concepts, in: Advances in Physical Organic Chemistry, edited by: Williams, I. H., and Williams, N. H., Academic Press, 29-68, https://doi.org/10.1016/bs.apoc.2019.09.001, 2019.

Tyburski, R., Liu, T. F., Glover, S. D., and Hammarström, L.: Proton-Coupled Electron Transfer Guidelines, Fair and Square, Journal of the American Chemical Society, 143, 560-576, 10.1021/jacs.0c09106, 2021.

Uesawa, Y.: Progress in Predicting Ames Test Outcomes from Chemical Structures: An In-Depth Re-Evaluation of Models from the 1st and 2nd Ames/QSAR International Challenge Projects, International Journal of Molecular Sciences, 25, 1373, 2024.

Van Der Spoel, D., Lindahl, E., Hess, B., Groenhof, G., Mark, A. E., and Berendsen, H. J. C.: GROMACS: Fast, flexible, and free, Journal of Computational Chemistry, 26, 1701-1718, https://doi.org/10.1002/jcc.20291, 2005.

Vereecken, L. and Francisco, J. S.: Theoretical studies of atmospheric reaction mechanisms in the troposphere, Chemical Society Reviews, 41, 6259-6293, 10.1039/c2cs35070j, 2012.

vom Eyser, C., Börgers, A., Richard, J., Dopp, E., Janzen, N., Bester, K., and Tuerk, J.: Chemical and toxicological evaluation of transformation products during advanced oxidation processes, Water Science and Technology, 68, 1976-1983, 10.2166/wst.2013.452, 2013.

Wang, C. L., Zhao, N., Ma, Z. J., He, M. X., Hou, C. X., and Sun, J. F.: Unraveling the heterogeneous reaction of 4-nitrocatechol with ozone in the atmosphere: A combined DFT, molecular dynamics, and environmental risk assessment, Atmospheric Research, 331, 10.1016/j.atmosres.2025.108632, 2026.

Wang, J., Wolf, R. M., Caldwell, J. W., Kollman, P. A., and Case, D. A.: Development and testing of a general amber force field, J Comput Chem, 25, 1157-1174, 10.1002/jcc.20035, 2004.

Witt, R. P., Todd, M. B., Oladele, M. E., and Guzman, M. I.: Ozonolysis of phenolic aldehydes from industrial-based lignin wastewaters, Sci Total Environ, 998, 180190, 10.1016/j.scitotenv.2025.180190, 2025.

Yan, J. P., Wang, X. P., Gong, P., and Wang, C. F.: Nitrated polycyclic aromatic compounds in the atmospheric environment: A review, Critical Reviews in Environmental Science and Technology, 51, 1159-1185, 10.1080/10643389.2020.1748486, 2021.

Yang, B., Ren, P. P., Xing, L., Wang, S. H., and Sun, C. L.: Roles of hydrogen bonding interactions and hydrophobic effects on enhanced water structure in aqueous solutions of amphiphilic organic molecules, Spectrochimica Acta Part a-Molecular and Biomolecular Spectroscopy, 296, 10.1016/j.saa.2023.122605, 2023a.

Yang, B. R., Liang, A. B., and Wang, L. M.: The atmospheric oxidation mechanism of acetophenone initiated by the hydroxyl radicals, Atmospheric Environment, 309, 10.1016/j.atmosenv.2023.119905, 2023b.

Yong-di, H. E., Jin-ou, S., Bin, W. U., Xiao-wen, W., Ji-biao, X. I. E., and Bin, W.: Prediction of toxicity of nitro-organic compounds by Toxicity Estimation Software Tool and Toxtree software, Chinese Journal of Pharmacology and Toxicology, 36, 509-520, 10.3867/j.issn.1000-3002.2022.07.005, 2022.

Young, D., Martin, T., Venkatapathy, R., and Harten, P.: Are the Chemical Structures in Your QSAR Correct? Qsar & Combinatorial Science, 27, 1337-1345, 10.1002/qsar.200810084, 2008.

Zhao, Y. and Truhlar, D. G.: The M06 suite of density functionals for main group thermochemistry, thermochemical kinetics, noncovalent interactions, excited states, and

transition elements: two new functionals and systematic testing of four M06-class functionals and 12 other functionals, Theoretical Chemistry Accounts, 120, 215-241, 10.1007/s00214-007-0310-x, 2008.

Al-Abadleh, H. A., Motaghedi, F., Mohammed, W., Rana, M. S., Malek, K. A., Rastogi, D., Asa-Awuku, A. A., and Guzman, M. I.: Reactivity of aminophenols in forming nitrogen-containing brown carbon from iron-catalyzed reactions, Commun Chem, 5, 112, 10.1038/s42004-022-00732-1, 2022.

Albinet, A., Minero, C., and Vione, D.: Phototransformation processes of 2,4-dinitrophenol, relevant to atmospheric water droplets, Chemosphere, 80, 753-758, 10.1016/j.chemosphere.2010.05.016, 2010.

Andreae, M. O. and Gelencsér, A.: Black carbon or brown carbon? The nature of light-absorbing carbonaceous aerosols, Atmos. Chem. Phys., 6, 3131-3148, 10.5194/acp-6-3131-2006, 2006.

Athar, M. and Patnaik, A.: Through-Bond-Driven Through-Space Interactions in a Fullerene C60 Noncovalent Dyad: An Unusual Strong Binding between Spherical and Planar π Electron Clouds and Culmination of Dyadic Fractals, Journal of Physical Chemistry A, 126, 3629-3641, 10.1021/acs.jpca.1c10828, 2022.

Atkinson, R., Tuazon, E. C., Wallington, T. J., Aschmann, S. M., Arey, J., Winer, A. M., and Pitts, J. N.: Atmospheric chemistry of aniline, N,N-dimethylaniline, pyridine, 1,3,5-triazine, and nitrobenzene, Environmental Science & Technology, 21, 64-72, 10.1021/es00155a007, 1987.

Bejan, I., Barnes, I., Olariu, R., Zhou, S., Wiesen, P., and Benter, T.: Investigations on the gas-phase photolysis and OH radical kinetics of methyl-2-nitrophenols, Physical Chemistry Chemical Physics, 9, 5686-5692, 10.1039/b709464g, 2007.

Benfenati, E., Benigni, R., DeMarini, D. M., Helma, C., Kirkland, D., Martin, T. M., Mazzatorta, P., Ouédraogo-Arras, G., Richard, A. M., Schilter, B., Schoonen, W., Snyder, R., and Yang, C.: Predictive Models for Carcinogenicity and Mutagenicity: Frameworks, State-of-the-Art, and Perspectives, Journal of Environmental Science and Health Part C-Environmental Carcinogenesis & Ecotoxicology Reviews, 27, 57-90, 10.1080/10590500902885593, 2009.

Benigni, R., Bossa, C., Netzeva, T., Rodomonte, A., and Tsakovska, I.: Mechanistic QSAR of aromatic amines: new models for discriminating between homocyclic mutagens and nonmutagens, and validation of models for carcinogens, Environ Mol Mutagen, 48, 754-771, 10.1002/em.20355, 2007.

Calvert, J. G., Orlando, J. J., Stockwell, W. R., and Wallington, T. J.: The Mechanisms of Reactions Influencing Atmospheric Ozone, Oxford University Press, 10.1093/oso/9780190233020.001.0001, 2015.

Canneaux, S., Bohr, F., and Henon, E.: KiSThelP: A Program to Predict Thermodynamic Properties and Rate Constants from Quantum Chemistry Results, Journal of Computational Chemistry, 35, 82-93, 10.1002/jcc.23470, 2014.

Cassano, A., Manganaro, A., Martin, T., Young, D., Piclin, N., Pintore, M., Bigoni, D., and Benfenati, E.: CAESAR models for developmental toxicity, Chemistry Central Journal, 4, 10.1186/1752-153x-4-s1-s4, 2010.

Chapleski, R. C., Zhang, Y. F., Troya, D., and Morris, J. R.: Heterogeneous chemistry and reaction dynamics of the atmospheric oxidants, O3, NO3, and OH, on organic surfaces, Chemical Society Reviews, 45, 3731-3746, 10.1039/c5cs00375j, 2016.

Cornelissen, G., Gustafsson, O., Bucheli, T. D., Jonker, M. T. O., Koelmans, A. A., and M van Noort, P. C.: Extensive sorption of organic compounds to black carbon, coal, and kerogen in sediments and soils: mechanisms and consequences for distribution, bioaccumulation, and biodegradation, Environmental Science and Technology, 39, 10.1021/es050191b, 2005.

Cramer, G. M., Ford, R. A., and Hall, R. L.: Estimation of toxic hazard—A decision tree approach, Food and Cosmetics Toxicology, 16, 255–276, https://doi.org/10.1016/S0015-6264(76)80522-6, 1976.

Decesari, S., Kovarich, S., Pavan, M., Bassan, A., Ciacci, A., and Topping, D.: Evaluating the mutagenic potential of aerosol organic compounds using informatics-based screening, Atmos. Chem. Phys., 18, 2329–2340, 10.5194/acp-18-2329-2018, 2018.

Delaria, E. R. and Cohen, R. C.: Measurements of Atmosphere–Biosphere Exchange of Oxidized Nitrogen and Implications for the Chemistry of Atmospheric NO x, Accounts of Chemical Research, 56, 1720–1730, 10.1021/acs.accounts.3c00090, 2023.

EPA, U. S.: User's Guide for T.E.S.T. (version 5.1) (Toxicity Estimation Software Tool): A Program to Estimate Toxicity from Molecular Structure., U.S. Environmental Protection Agency, 2020.

Fan, W. L., Chen, T., Zhu, Z. L., Zhang, H., Qiu, Y. L., and Yin, D. Q.: A review of secondary organic aerosols formation focusing on organosulfates and organic nitrates, Journal of Hazardous Materials, 430, 10.1016/j.jhazmat.2022.128406, 2022.

Frisch, M. J., Trucks, G. W., Schlegel, H. B., Scuseria, G. E., Robb, M. A., Cheeseman, J. R., Scalmani, G., Barone, V., Petersson, G. A., Nakatsuji, H., Li, X., Caricato, M., Marenich, A. V., Bloino, J., Janesko, B. G., Gomperts, R., Mennucci, B., Hratchian, H. P., Ortiz, J. V., Izmaylov, A. F., Sonnenberg, J. L., Williams, Ding, F., Lipparini, F., Egidi, F., Goings, J., Peng, B., Petrone, A., Henderson, T., Ranasinghe, D., Zakrzewski, V. G., Gao, J., Rega, N., Zheng, G., Liang, W., Hada, M., Ehara, M., Toyota, K., Fukuda, R., Hasegawa, J., Ishida, M., Nakajima, T., Honda, Y., Kitao, O., Nakai, H., Vreven, T., Throssell, K., Montgomery Jr., J. A., Peralta, J. E., Ogliaro, F., Bearpark, M. J., Heyd, J. J., Brothers, E. N., Kudin, K. N., Staroverov, V. N., Keith, T. A., Kobayashi, R., Normand, J., Raghavachari, K., Rendell, A. P., Burant, J. C., Iyengar, S. S., Tomasi, J., Cossi, M., Millam, J. M., Klene, M., Adamo, C., Cammi, R., Ochterski, J. W., Martin, R. L., Morokuma, K., Farkas, O., Foresman, J. B., and Fox, D. J.: Gaussian 16 Rev. C.01 [code], 2016.

Geyer, A., Bächmann, K., Hofzumahaus, A., Holland, F., Stefan, Konrad, Klüpfel, T., Pätz, H. W., Perner, D., Mihelcic, D., Schäfer, H. J., Volz-Thomas, A., and Platt, U.: Nighttime formation of peroxy and hydroxyl radicals during the BERLIOZ campaign: Observations and modeling studies, Journal of Geophysical Research, 108, 8249, 2003.

Guzman, M. I., Pillar-Little, E. A., and Eugene, A. J.: Interfacial Oxidative Oligomerization of Catechol, ACS Omega, 7, 36009–36016, 10.1021/acsomega.2c05290, 2022.

Hems, R. F. and Abbatt, J. P. D.: Aqueous Phase Photo-oxidation of Brown Carbon Nitrophenols: Reaction Kinetics, Mechanism, and Evolution of Light Absorption, ACS Earth and Space Chemistry, 2, 225–234, 10.1021/acsearthspacechem.7b00123, 2018.

Humphrey, W., Dalke, A., and Schulten, K.: VMD: Visual molecular dynamics, Journal of Molecular Graphics, 14, 33–38, https://doi.org/10.1016/0263-7855(96)00018-5, 1996.

Khan, M. A. H., Hoque, M. M. N., Alam, S. S., Ashfold, M. J., Nickless, G., and Shallcross, D. E.: Estimation and comparison of night-time OH levels in the UK urban atmosphere using two different analysis methods, Journal of Environmental Sciences, 23, 60–64, https://doi.org/10.1016/S1001-0742(10)60373-7, 2011.

Kroll, J. H. and Seinfeld, J. H.: Chemistry of secondary organic aerosol: Formation and evolution of low-volatility organics in the atmosphere, Atmospheric Environment, 42, 3593-3624, 10.1016/j.atmosenv.2008.01.003, 2008.
Kromann, J. C., Steinmann, C., and Jensen, J. H.: Improving solvation energy predictions using the SMD solvation method and semiempirical electronic structure methods, Journal of Chemical Physics, 149, 10.1063/1.5047273, 2018.
Lefebvre, C., Rubez, G., Khartabil, H., Boisson, J. C., Contreras-García, J., and Hénon, E.: Accurately extracting the signature of intermolecular interactions present in the NCI plot of the reduced density gradient versus electron density, Physical Chemistry Chemical Physics, 19, 17928-17936, 10.1039/c7cp02110k, 2017.
Li, J., Han, Z. W., Sun, Y. L., Li, J. W., and Liang, L.: Chemical formation pathways of secondary organic aerosols in the Beijing-Tianjin-Hebei region in wintertime, Atmospheric Environment, 244, 10.1016/j.atmosenv.2020.117996, 2021.
Li, J., Han, Z. W., Wu, J., Tao, J., Li, J. W., Sun, Y. L., Liang, L., Liang, M. J., and Wang, Q. G.: Secondary organic aerosol formation and source contributions over east China in summertime, Environmental Pollution, 306, 10.1016/j.envpol.2022.119383, 2022a.
Li, M., Wang, X. F., Lu, C. Y., Li, R., Zhang, J., Dong, S. W., Yang, L. X., Xue, L. K., Chen, J. M., and Wang, W. X.: Nitrated phenols and the phenolic precursors in the atmosphere in urban Jinan, China, Science of the Total Environment, 714, 10.1016/j.scitotenv.2020.136760, 2020.
Li, M., Wang, X. F., Zhao, Y. N., Du, P., Li, H. Y., Li, J. R., Shen, H. Q., Liu, Z. Y., Jiang, Y. R., Chen, J., Bi, Y. J., Zhao, Y., Xue, L. K., Wang, Y., Chen, J. M., and Wang, W. X.: Atmospheric Nitrated Phenolic Compounds in Particle, Gaseous, and Aqueous Phases During Cloud Events at a Mountain Site in North China: Distribution Characteristics and Aqueous-Phase Formation, Journal of Geophysical Research-Atmospheres, 127, 10.1029/2022jd037130, 2022b.
Li, P. Y., Feng, L., Li, G. Y., and Bai, F. Q.: Effects of Electron Donating Ability of Substituents and Molecular Conjugation on the Electronic Structures of Organic Radicals, Chemical Research in Chinese Universities, 39, 202-207, 10.1007/s40242-023-2364-2, 2023.
Lindorff-Larsen, K., Piana, S., Palmo, K., Maragakis, P., Klepeis, J. L., Dror, R. O., and Shaw, D. E.: Improved side-chain torsion potentials for the Amber ff99SB protein force field, Proteins, 78, 1950-1958, 10.1002/prot.22711, 2010.
Liu, Z. Y. and Lu, T.: Theoretical Insight into Complexation Between Cyclocarbons and C60 Fullerene, Chemistry-a European Journal, 30, 10.1002/chem.202402227, 2024.
TST calculator: http://sobereva.com/310, last access: Dec 11.
Lu, T.: Sobtop (2026.1.16) [code], 2026.
Lu, T. and Chen, F. W.: Multiwfn: A multifunctional wavefunction analyzer, Journal of Computational Chemistry, 33, 580-592, 10.1002/jcc.22885, 2012.
Lu, T. and Chen, Q. X.: Independent gradient model based on Hirshfeld partition: A new method for visual study of interactions in chemical systems, Journal of Computational Chemistry, 43, 539-555, 10.1002/jcc.26812, 2022.
Lüttke, J. and Levsen, K.: Phase partitioning of phenol and nitrophenols in clouds, Atmospheric Environment, 31, 2649-2655, https://doi.org/10.1016/S1352-2310(96)00228-2, 1997.
Lyu, Y., Xu, H., Yuan, H. X., Cui, Y. L., Zhang, C. Z., and Meng, Q. T.: Intermolecular interaction mechanisms between dinitrophenol and water: a molecular dynamics and DFT study, European Physical Journal Plus, 140, 10.1140/epjp/s13360-025-06478-8, 2025.

Maeda, S., Harabuchi, Y., Ono, Y., Taketsugu, T., and Morokuma, K.: Intrinsic Reaction Coordinate: Calculation, Bifurcation, and Automated Search, International Journal of Quantum Chemistry, 115, 258–269, 10.1002/qua.24757, 2015.

Mahilang, M., Deb, M. K., and Pervez, S.: Biogenic secondary organic aerosols: A review on formation mechanism, analytical challenges and environmental impacts, Chemosphere, 262, 10.1016/j.chemosphere.2020.127771, 2021.

Mayer, J. M.: Understanding hydrogen atom transfer: from bond strengths to Marcus theory, Accounts of chemical research, 44, 36–46, 10.1021/ar100093z, 2011.

McNeill, V. F.: Atmospheric Aerosols: Clouds, Chemistry, and Climate, Annual Review of Chemical and Biomolecular Engineering, 8, 10.1146/annurev-chembioeng-060816-101538, 2017.

Miyoshi, A., Matsui, H., and Washida, N.: Rates of reaction of hydroxyalkyl radicals with molecular oxygen, The Journal of Physical Chemistry, 94, 3016–3019, 1990.

Morgan, C. A., Pilling, M. J., Tulloch, J. M., Ruiz, R. P., and Bayes, K. D.: DIRECT DETERMINATION OF THE EQUILIBRIUM CONSTANT AND THERMODYNAMIC PARAMETERS FOR THE REACTION ALLYL RADICAL + OXYGEN ⇌ ALLYLPEROXY RADICAL, ChemInform, 13, 1982.

Munro, I. C., Ford, R. A., Kennepohl, E., and Sprenger, J. G.: Correlation of structural class with no-observed-effect levels: A proposal for establishing a threshold of concern, Food and Chemical Toxicology, 34, 829–867, https://doi.org/10.1016/S0278-6915(96)00049-X, 1996.

Nagy, P. R.: State-of-the-art local correlation methods enable affordable gold standard quantum chemistry for up to hundreds of atoms, Chem Sci, 15, 14556–14584, 10.1039/d4sc04755a, 2024.

Ng, N. L., Brown, S. S., Archibald, A. T., Atlas, E., Cohen, R. C., Crowley, J. N., Day, D. A., Donahue, N. M., Fry, J. L., Fuchs, H., Griffin, R. J., Guzman, M. I., Herrmann, H., Hodzic, A., Iinuma, Y., Jimenez, J. L., Kiendler-Scharr, A., Lee, B. H., Luecken, D. J., Mao, J., McLaren, R., Mutzel, A., Osthoff, H. D., Ouyang, B., Picquet-Varrault, B., Platt, U., Pye, H. O. T., Rudich, Y., Schwantes, R. H., Shiraiwa, M., Stutz, J., Thornton, J. A., Tilgner, A., Williams, B. J., and Zaveri, R. A.: Nitrate radicals and biogenic volatile organic compounds:<?xmltex \hack{ }?> oxidation, mechanisms, and organic aerosol, Atmospheric Chemistry & Physics, 17, 2103–2162, 10.5194/acp-17-2103-2017, 2017.

Patlewicz, G., Jeliazkova, N., Safford, R. J., Worth, A. P., and Aleksiev, B.: An evaluation of the implementation of the Cramer classification scheme in the Toxtree software, SAR and QSAR in environmental research, 19, 495–524, 10.1080/10629360802083871, 2008.

Perumpully, S. J. and Gautam, S.: Impact of aerosols on atmospheric processes and climate variability: A synthesis of recent research findings, Geosystems and Geoenvironment, 4, 100317, https://doi.org/10.1016/j.geogeo.2024.100317, 2025.

Pillar-Little, E. A. and Guzman, M. I.: Oxidation of Substituted Catechols at the Air–Water Interface: Production of Carboxylic Acids, Quinones, and Polyphenols, Environmental Science & Technology, 51, 4951–4959, 10.1021/acs.est.7b00232, 2017.

Pillar-Little, E. A. and Guzman, M. I.: An Overview of Dynamic Heterogeneous Oxidations in the Troposphere, Environments, 5, 104, 2018.

Pillar-Little, E. A., Camm, R. C., and Guzman, M. I.: Catechol oxidation by ozone and hydroxyl radicals at the air-water interface, Environ Sci Technol, 48, 14352–14360, 10.1021/es504094x, 2014.

Pillar, E. A., Camm, R. C., and Guzman, M. I.: Catechol Oxidation by Ozone and Hydroxyl Radicals

at the Air–Water Interface, Environmental Science & Technology, 48, 14352–14360, 10.1021/es504094x, 2014.
Pillar, E. A., Zhou, R., and Guzman, M. I.: Heterogeneous Oxidation of Catechol, Journal of Physical Chemistry A, 119, 10349–10359, 10.1021/acs.jpca.5b07914, 2015.
Pino-Rios, R., Inostroza, D., Cárdenas-Jirón, G., and Tiznado, W.: Orbital-Weighted Dual Descriptor for the Study of Local Reactivity of Systems with (Quasi-) Degenerate States, Journal of Physical Chemistry A, 123, 10556–10562, 10.1021/acs.jpca.9b07516, 2019.
Poster, D., Nguyen, T., Brown, R., and Ball, W.: Evidence for a pore-filling mechanism in the adsorption of aromatic hydrocarbons to a natural wood char, https://doi.org/10.1021/es0617845, 2007.
Qin, M., Xie, P., Su, H., Gu, J., Peng, F., Li, S., Zeng, L., Liu, J., Liu, W., and Zhang, Y.: An observational study of the HONO–NO2 coupling at an urban site in Guangzhou City, South China, Atmospheric Environment, 43, 5731–5742, https://doi.org/10.1016/j.atmosenv.2009.08.017, 2009.
Rana, M. S. and Guzman, M. I.: Oxidation of Phenolic Aldehydes by Ozone and Hydroxyl Radicals at the Air–Water Interface, The Journal of Physical Chemistry A, 124, 8822–8833, 10.1021/acs.jpca.0c05944, 2020.
Rana, M. S. and Guzman, M. I.: Oxidation of Phenolic Aldehydes by Ozone and Hydroxyl Radicals at the Air–Solid Interface, ACS Earth Space Chem, 6, 2900–2909, 10.1021/acsearthspacechem.2c00206, 2022a.
Rana, M. S. and Guzman, M. I.: Oxidation of Catechols at the Air-Water Interface by Nitrate Radicals, Environ Sci Technol, 56, 15437–15448, 10.1021/acs.est.2c05640, 2022b.
Rana, M. S. and Guzman, M. I.: Mechanistic Insights into Heterogeneous Oxidation: Product-Resolved Analysis of Phenolic Aldehyde Films, ACS Physical Chemistry Au, 2026a.
Rana, M. S. and Guzman, M. I.: Heterogeneous Nitrate Radical Oxidation of Catechol Produces Nitrocatechols, Oligomers, and Brown Carbon, ACS Earth & Space Chemistry, 10, 2159 – 2170, 2026b.
Rana, M. S., Bradley, S. T., and Guzman, M. I.: Conversion of Catechol to 4-Nitrocatechol in Aqueous Microdroplets Exposed to O3 and NO2, ACS ES&T Air, 1, 80–91, 10.1021/acsestair.3c00001, 2023.
Salvador, C. M. G., Tang, R. Z., Priestley, M., Li, L. J., Tsiligiannis, E., Le Breton, M., Zhu, W. F., Zeng, L. M., Wang, H., Yu, Y., Hu, M., Guo, S., and Hallquist, M.: Ambient nitro-aromatic compounds – biomass burning versus secondary formation in rural China, Atmospheric Chemistry and Physics, 21, 1389–1406, 10.5194/acp-21-1389-2021, 2021.
Schwarzenbach, R. P., Stierli, R., Folsom, B. R., and Zeyer, J.: Compound properties relevant for assessing the environmental partitioning of nitrophenols, 22:1, 10.1021/es00166a009 Journal Name: Environ. Sci. Technol.; (United States) Journal Volume: 22:1, 1988.
Shenghur, A., Weber, K. H., Nguyen, N. D., Sontising, W., and Tao, F. M.: Theoretical Study of the Hydrogen Abstraction of Substituted Phenols by Nitrogen Dioxide as a Source of HONO, Journal of Physical Chemistry A, 118, 11002–11014, 10.1021/jp508516c, 2014.
Shi, K., Mei, X. L., Chen, C. R., and Liu, C. Q.: Impact of atmospheric O3 and NO2 on the secondary sulfates in real atmosphere, Journal of Environmental Sciences, 150, 277–287, 10.1016/j.jes.2024.02.019, 2025.
Shirts, M. R., Pitera, J. W., Swope, W. C., and Pande, V. S.: Extremely precise free energy

calculations of amino acid side chain analogs: Comparison of common molecular mechanics force fields for proteins, Journal of Chemical Physics, 119, 5740-5761, 10.1063/1.1587119, 2003.
Shukla, S. S., Dorris, K. L., and Chikkaveeraiah, B. V.: Photocatalytic degradation of 2,4-dinitrophenol, Journal of Hazardous Materials, 164, 310-314, 10.1016/j.jhazmat.2008.08.047, 2009.
Spiegel, M., Semidalas, E., Martin, J. M. L., Bentley, M. R., and Stanton, J. F.: Post-CCSD(T) corrections to bond distances and vibrational frequencies: the power of A, Molecular Physics, 122, 10.1080/00268976.2023.2252114, 2024.
Steiner, T.: The Hydrogen Bond in the Solid State, Angewandte Chemie International Edition, 41, 48-76, https://doi.org/10.1002/1521-3773(20020104)41:1<48::AID-ANIE48>3.0.CO;2-U, 2002.
Sun, J., Mu, Q., Kimura, H., Murugadoss, V., He, M., Du, W., and Hou, C.: Oxidative degradation of phenols and substituted phenols in the water and atmosphere: a review, Advanced Composites and Hybrid Materials, 5, 627-640, 2022.
Sushko, I., Novotarskyi, S., Körner, R., Pandey, A. K., Cherkasov, A., Li, J., Gramatica, P., Hansen, K., Schroeter, T., Müller, K. R., Xi, L., Liu, H., Yao, X., Öberg, T., Hormozdiari, F., Dao, P., Sahinalp, C., Todeschini, R., Polishchuk, P., Artemenko, A., Kuz'min, V., Martin, T. M., Young, D. M., Fourches, D., Muratov, E., Tropsha, A., Baskin, I., Horvath, D., Marcou, G., Muller, C., Varnek, A., Prokopenko, V. V., and Tetko, I. V.: Applicability domains for classification problems: Benchmarking of distance to models for Ames mutagenicity set, J Chem Inf Model, 50, 2094-2111, 10.1021/ci100253r, 2010.
Szatylowicz, H., Jezuita, A., Ejsmont, K., and Krygowski, T. M.: Substituent Effect on the σ- and π-Electron Structure of the Nitro Group and the Ring in Meta- and Para-Substituted Nitrobenzenes, Journal of Physical Chemistry A, 121, 5196-5203, 10.1021/acs.jpca.7b03418, 2017.
Tam, J. Y. C., Lorsbach, T., Schmidt, S., and Wicker, J. S.: Holistic evaluation of biodegradation pathway prediction: assessing multi-step reactions and intermediate products, Journal of Cheminformatics, 13, 63, 10.1186/s13321-021-00543-x, 2021.
Tintó-Moliner, A. and Martin, M.: Quantitative weight of evidence method for combining predictions of quantitative structure-activity relationship models, SAR and QSAR in Environmental Research, 31, 261-279, 10.1080/1062936X.2020.1725116, 2020.
Tiwari, J., Tarale, P., Sivanesan, S., and Bafana, A.: Environmental persistence, hazard, and mitigation challenges of nitroaromatic compounds, Environmental Science and Pollution Research, 26, 28650-28667, 10.1007/s11356-019-06043-8, 2019.
Tomas, A., Olariu, R. I., Barnes, I., and Becker, K. H.: Kinetics of the reaction of O3 with selected benzenediols, International Journal of Chemical Kinetics, 35, 223-230, https://doi.org/10.1002/kin.10121, 2003.
Tuñón, I. and Williams, I. H.: Chapter Two - The transition state and cognate concepts, in: Advances in Physical Organic Chemistry, edited by: Williams, I. H., and Williams, N. H., Academic Press, 29-68, https://doi.org/10.1016/bs.apoc.2019.09.001, 2019.
Tyburski, R., Liu, T. F., Glover, S. D., and Hammarström, L.: Proton-Coupled Electron Transfer Guidelines, Fair and Square, Journal of the American Chemical Society, 143, 560-576, 10.1021/jacs.0c09106, 2021.
Uesawa, Y.: Progress in Predicting Ames Test Outcomes from Chemical Structures: An In-Depth Re-Evaluation of Models from the 1st and 2nd Ames/QSAR International Challenge Projects,

International Journal of Molecular Sciences, 25, 1373, 2024.
Van Der Spoel, D., Lindahl, E., Hess, B., Groenhof, G., Mark, A. E., and Berendsen, H. J. C.: GROMACS: Fast, flexible, and free, Journal of Computational Chemistry, 26, 1701–1718, https://doi.org/10.1002/jcc.20291, 2005.
Vereecken, L. and Francisco, J. S.: Theoretical studies of atmospheric reaction mechanisms in the troposphere, Chemical Society Reviews, 41, 6259–6293, 10.1039/c2cs35070j, 2012.
vom Eyser, C., Börgers, A., Richard, J., Dopp, E., Janzen, N., Bester, K., and Tuerk, J.: Chemical and toxicological evaluation of transformation products during advanced oxidation processes, Water Science and Technology, 68, 1976–1983, 10.2166/wst.2013.452, 2013.
Wang, C. L., Zhao, N., Ma, Z. J., He, M. X., Hou, C. X., and Sun, J. F.: Unraveling the heterogeneous reaction of 4-nitrocatechol with ozone in the atmosphere:A combined DFT, molecular dynamics, and environmental risk assessment, Atmospheric Research, 331, 10.1016/j.atmosres.2025.108632, 2026.
Wang, J., Wolf, R. M., Caldwell, J. W., Kollman, P. A., and Case, D. A.: Development and testing of a general amber force field, J Comput Chem, 25, 1157–1174, 10.1002/jcc.20035, 2004.
Witt, R. P., Todd, M. B., Oladele, M. E., and Guzman, M. I.: Ozonolysis of phenolic aldehydes from industrial-based lignin wastewaters, Sci Total Environ, 998, 180190, 10.1016/j.scitotenv.2025.180190, 2025.
Yan, J. P., Wang, X. P., Gong, P., and Wang, C. F.: Nitrated polycyclic aromatic compounds in the atmospheric environment: A review, Critical Reviews in Environmental Science and Technology, 51, 1159–1185, 10.1080/10643389.2020.1748486, 2021.
Yang, B., Ren, P. P., Xing, L., Wang, S. H., and Sun, C. L.: Roles of hydrogen bonding interactions and hydrophobic effects on enhanced water structure in aqueous solutions of amphiphilic organic molecules, Spectrochimica Acta Part a-Molecular and Biomolecular Spectroscopy, 296, 10.1016/j.saa.2023.122605, 2023a.
Yang, B. R., Liang, A. B., and Wang, L. M.: The atmospheric oxidation mechanism of acetophenone initiated by the hydroxyl radicals, Atmospheric Environment, 309, 10.1016/j.atmosenv.2023.119905, 2023b.
Yong-di, H. E., Jin-ou, S., Bin, W. U., Xiao-wen, W., Ji-biao, X. I. E., and Bin, W.: Prediction of toxicity of nitro-organic compounds by Toxicity Estimation Software Tool and Toxtree software, Chinese Journal of Pharmacology and Toxicology, 36, 509–520, 10.3867/j.issn.1000-3002.2022.07.005, 2022.
Young, D., Martin, T., Venkatapathy, R., and Harten, P.: Are the Chemical Structures in Your QSAR Correct?, Qsar & Combinatorial Science, 27, 1337–1345, 10.1002/qsar.200810084, 2008.
Zhao, Y. and Truhlar, D. G.: The M06 suite of density functionals for main group thermochemistry, thermochemical kinetics, noncovalent interactions, excited states, and transition elements: two new functionals and systematic testing of four M06-class functionals and 12 other functionals, Theoretical Chemistry Accounts, 120, 215–241, 10.1007/s00214-007-0310-x, 2008.