

Autoxidation of Glycols Used in Inhalable Daily Products: Implications to the Use of Artificial Fogs and E-cigarettes

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The data that support the findings of this study are available from the corresponding author upon reasonable request.

Conflict of Interest Statement

No conflict of interest was declared.

Author Contribution Statement

Xinyang Guo: Leading the project, Built up experimental procedures, Identified all carbonyl compounds in the sample, built up experimental procedures, processed all data, and written the manuscript.

Ya-Chun Chan: Contributed to the standard addition experiment of carbonyls, performed UV-Vis measurement of all glycols.

Tania Gautam: Providing details about iodometry and UV-Vis measurements.

Ran Zhao: The PI, oversaw the entire project with advice and proofread the manuscript.

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Abstract

The use of glycols is seen in various industries and occupations. In past decades, health implications from inhalable glycols have gained public attention. Inhalable glycols may cause adverse health effects, especially for workers in occupations receiving frequent exposure and consumers of glycol-based daily products. Our previous work highlighted the rapid accumulation of formaldehyde and glycolaldehyde in fog juice, thus proposing the occurrence of glycol autoxidation. However, the fundamentals of glycol autoxidation remained unclear and unexplored. Our goal is to investigate the autoxidation of common glycols during indoor storage. Carbonyls were quantified using liquid chromatography-mass spectrometry (LC-MS), and peroxides from autoxidation were monitored via iodometry and UV-Vis spectrometry. The impact of certain factors such as the water mixing ratio, and antioxidants (Vitamin C) was also investigated. Formation of aldehydes in many glycols was weekly monitored, such as E-cigarette juice and triethylene glycol (TEG). Occurrence of autoxidation was confirmed by the rise in the total peroxide concentration. Additionally, we highlighted the dependence

of carbonyl formation rate on the TEG-water mixing ratio, demonstrating the complex role water in glycol autoxidation. We have also tested the effectiveness of Vitamin C, with suggestions for minimizing the formation of toxic carbonyls in consumer products.

Introduction

Glycols, or diols, are families of alcohols that have two hydroxyl groups (-OH) attached to an aliphatic carbon chain. By having different lengths of the carbon chain, every glycol has its unique physical and chemical properties that make them useful in various industries and daily products. Due to the presence of multiple hydroxyl groups, glycol molecules have very strong intermolecular forces, which give rise to their low volatility and high viscosity. Conventionally, glycols are found in liquid or gel-like products, such as engine coolants,¹ drug delivery media,² food additives,³ as well as antifreeze or dehydrators.⁴ Recently, growing demand for glycols has been found in volatile organic compound-generating (VOC-generating) or inhalable products. Ethylene glycol (EG), diethylene glycol (DEG), triethylene glycol (TEG), and polyethylene glycol (PEG) are common constituents in products including wall paints,⁵ artificial fog juice,⁶ and perfumes. Glycerol (VG) and propylene glycol (PG) are mostly seen in food or drug additives, solvents of personal care products, and E-cigarette juice.⁷⁻¹⁰ Especially, as the indoor environment becomes where people spend the majority of their daily life, the aforementioned inhalable products could lead to elevated human exposure to glycols and potentially other harmful compounds, leaving a strong implication for indoor air quality. Especially for occupations under frequent glycol exposure, the adverse health effects and productivity loss due to elevated indoor air pollutants could be significant.^{11,12}

With the development of the entertainment industry and vaping industry in recent decades,¹³ individual and public health implications of inhalable glycols have garnered more attention from consumers and researchers. Since the early 2000s, a few studies proposed that stage actors may experience adverse health effects due to the high exposure of glycols in artificial fog.^{14,15} Wieslander et al. discovered that exposure to propylene glycol mist during

aviation training would cause respiratory system-related symptoms.¹⁶ However, not many studies have addressed the origin of the health impact of glycol exposure in the following decade. In the past years, emerging e-cigarette and vaping-associated lung injuries (EVALI) became a serious health concern among the young population in North America.^{17,18} Many e-cigarette-related studies have proposed that the thermal degradation of glycol in e-cigarette juice will produce various toxic aldehydes, such as formaldehyde.^{19,20} The degradation is found under high-temperature settings of the heating coil.^{21,22} Thermal degradation may not be the only cause of the carbonyls in glycols, as carbonyls were also discovered under milder coil temperatures.²³ Meanwhile, studies also proposed aldehyde formation from autoxidation of poly-glycols,^{24–26} but no subsequent research has been systematically carried out since then. Consequently, the potential of various glycols forming toxic compounds via autoxidation during storage remains unknown, which may have implications for indoor environmental chemistry, consumer health, and occupational health.

Autoxidation is a spontaneous oxidative process of chemicals when exposed to air, it is initiated by oxidative radicals and propagated via peroxide-involved radical chemistry.²⁷ Autoxidation is first known in the condensed phase, which is the cause of the deterioration of many daily consumables, such as cooking oil,^{28,29} and foods.^{30,31} A decade ago, gas-phase autoxidation of VOCs was discovered by Crounse et al.³² Sooner this process has been identified as the critical process to produce highly oxygenated organic molecules, including the production of carbonyls and organic acids from biogenic gaseous monoterpenes.^{33–35} While autoxidation was associated with numerous compounds, such chemical processes on glycols did not gather enough attention in the past. Additionally, the oxidation of TEG is one of the major concerns in the natural gas dehydration industry,³⁶ leading to significantly reduced productivity. The aliphatic nature of glycols, i.e., lack of unsaturated bonds, makes them relatively less reactive to oxidative electrophiles (radicals, O_3), which are usually the initiators of autoxidation.³⁷ Our previous work, however, was the first to discover the formation of glycolaldehyde and formaldehyde from glycol-based fog machine juices during their

storage and proposed evidence of autoxidation.³⁸ Glycolaldehyde and formaldehyde are two toxic carbonyls found in the indoor air.³⁹ These aldehydes are often released indoors as the product of organic combustion, bacterial activity, or atmospheric oxidation.^{40–43}

Our previous study also highlighted the need to find stronger evidence for the occurrence of autoxidation, as well as the conditions under which autoxidation is favored. The presence of peroxide is an indicator of autoxidation, whose concentration reflects the extent and the rate of reaction. It can be quantified via certain mass spectrometric techniques,^{44–47} but the canonical method for total peroxide quantification has been iodometry.^{48–50} Iodometry is usually based on UV-Vis spectrometry because I^- reacts selectively and quantitatively with organic peroxides in the sample, and the resulting triiodide ion (I_3^-) has a unique absorption, peaking at 351 nm. This feature makes iodometry a sensitive and selective method to quantify the total peroxide concentration.⁵¹

The objective of this work is to systematically investigate the autoxidation of common glycols during storage under room conditions and to discover its implications on indoor air quality, product safety, and occupational health across various industries. Specifically, we aim to quantify the formation of harmful end-products of autoxidation, such as formaldehyde and glycolaldehyde. Moreover, iodometry will be conducted to monitor peroxide intermediates, and thus, the occurrence of autoxidation. Beyond these fundamental chemical analyses, we would also investigate the effect of external factors, such as the water mixing ratio or the presence of antioxidants, to provide suggestions to mitigate such risks of autoxidation in glycol products.

Material and Methods

Chemicals and Materials

MilliQ water used in this study was generated by a Thermo-Fisher Scientific Barnstead™ E-Pure™ Ultrapure Water Purification Systems. Reagent grade 2,4-dinitrophenyl hydrazine

(2,4-DNPH) (Purity 97%) was purchased from Alpha Aesar, and propylene glycol was purchased from Fisher Scientific. Acetonitrile (HPLC-grade, Purity 99.9%), triethylene glycol (TEG, Purity 99%), diethylene glycol (DEG, Purity 99%), glycerol (VG, Purity 99.5%) hydroquinone (Purity 99%), L-ascorbic acid (Vitamin C, Purity 99%), 37% formaldehyde in water solution (with 10-15% methanol), glycolaldehyde dimer (Crystalline), propionaldehyde (Purity 97%) were purchased from Sigma-Aldrich. A commercially available E-cigarette juice (EJ) is acquired from a local vape shop and contains 1:1 PG-VG and 10 mg/ml nicotine. Potassium iodide (KI) was purchased from Fisher Scientific. Hydrogen peroxide in water (30% w/w), and glacier acetic acid were purchased from Sigma-Aldrich.

Choice of Glycols

All the experimented glycols in the current study are listed in Table 1. Triethylene glycol was selected to further investigate the fundamental of glycol autoxidation because it demonstrated a significant formation of carbonyl from our previous study.³⁸ Additionally, PG and VG were selected for their common use in inhalable products, including EJ. DEG, the smallest poly-glycol commonly used as a food and drug additive, was selected to be compared with TEG, given their chain length difference. Finally, an EJ was also tested in this study to observe autoxidation in an actual product. We note that the EJ was chosen to have no additives besides PG and VG (10 mg/ml nicotine, and flavorless) to minimize unknown side reactions.

Sample preparation

The summary of sample preparation of the following three subsections is illustrated in Figure S1 in the Supplementary Information. All aging experiments listed below were conducted over 7-8 weeks. All samples were stored under room conditions in a typical chemistry laboratory, with temperature controlled at around 22 °C. Sampling activity was carried out at least once weekly, with occasionally more frequent sampling. Before sampling, all samples were

141 stirred on magnetic stir plates for at least five minutes to homogenize the glycol mixture.

142 **Aging of Glycols**

143 Two aging experiments were conducted to monitor the autoxidation of different glycols. The
144 first aging experiment (Exp. 1) was conducted with two groups of samples, referred to as
145 air-exposed samples or sealed samples. Each group of samples had five glass vials filled
146 with 20 ml of each glycol, as shown in Table 1 (TEG, PG, VG, DEG, and EJ) without
147 any dilution or modification. Air-exposed samples were stored without caps, which allowed
148 constant exposure to room air. Sealed samples were kept inside the vial with caps and
149 parafilm. The EJ sample in the sealed group was capped in its original package bottle and
150 sampled by directly squeezing it out. Additionally, sealed samples only had air exposure for
151 roughly 30 seconds during each sampling activity.

152 **Effect of Water Mixing Ratios**

153 Exp. 2 was designed to understand whether mixing with water would affect the rate of
154 glycol autoxidation. A set of TEG-water mixtures with increasing mixing ratios of water
155 (10%, 30%, 50%, and 70% of water) was prepared. The pure TEG sample mentioned in the
156 previous section also served as 0% water when making the comparison.

157 As we discovered a variation across different water mixing ratios from Exp. 2, we repeated
158 the measurement of 50% TEG in a separate experiment (Exp.3) as a detailed investigation.
159 A triplicate set of air-exposed TEG samples, mixed with 50% (v/v) water was prepared in
160 the same glass vials. This water ratio was selective as we later discovered that the 50% water
161 mixing ratio has the most rapid formation of carbonyls. Also, this mixing ratio represents
162 commercial fog juice, as their water ratio may vary between 40% to 60%. For the negative
163 control group, we prepared the same 50% (v/v) sample and sealed it as described previously.

Effect of Antioxidants

This experiment (Exp. 4) was designed based on the hypothesis that antioxidants can suppress the autoxidation process in glycol mixtures. There are many types of antioxidants studied previously,^{26,28,52} Vitamin C (L-ascorbic acid) was selected as the antioxidant used in our experiment, as it is an inexpensive and naturally existing antioxidant that can be found in many consumables and in the human body.⁵³ Due to its ability to react with a wide range of oxidants, it is considered the total reactive oxygen species scavenger.^{54,55} Although the inhalation risk of Vitamin C aerosols remains unclear, some studies show that the inhalation of Vitamin C is not harmful at proper dosages.^{56,57} Vitamin C was added directly into the air-exposed 50%-TEG water mixture, resulting in a concentration of 60 mM. This concentration is selected to ensure that antioxidant concentration is at least 10 times higher than that of peroxides determined in our sample, such that Vitamin C would not be consumed entirely during the aging experiment.

Derivatization by 2,4-DNPH

The quantification of carbonyl compounds in this study primarily depended on a derivatization reaction with 2,4-DNPH. 2,4-DNPH, or Brady's reagent, is one of the most widely used chemicals to measure small carbonyl compounds.^{58,59} The specific methodology was adapted from our previous study,³⁸ and thus is introduced only briefly here. A 2,4-DNPH working stock solution was prepared before any of the analyses. It was a 1:1 (v/v) water-acetonitrile solution containing 10 mM 2,4-DNPH and acidified by concentrated HCl, resulting in a pH of 3.0. Glycols mentioned above were derivatized using the same method. Samples were prepared in autosampler vials directly, each vial consisted of a diluted 2,4-DNPH working solution (20% of the total volume, 2 mM final concentration) and the glycol (2% of the total volume), a propionaldehyde internal standard (380 μ M in the sample), and a spiked carbonyl standard (20% of the total volume) for standard addition, as explained below. All samples were derivatized in a 25°C-water bath for 2 hours. According to our previous work,

the reaction will reach completion in 2 hours,³⁸ and neither a significant growth nor decay of the hydrazone chromatogram peak was observed within 24 hours.

Standard Addition of Carbonyls

The method of standard addition was used to identify and quantify the formaldehyde and glycolaldehyde in all samples, which can correct the fluctuation of derivatization efficiency among samples. Carbonyl standards were prepared at five concentrations, such that their final concentrations in autosampler vials ranged from 0 μ M to 50 μ M. Standard solutions only contain formaldehyde and glycolaldehyde, it was prepared by dissolving formaldehyde (37% water solution) and glycolaldehyde (crystalline dimer) into a 50% ACN solution. This stock solution was then diluted to the correct concentrations. Standard solutions were refreshed monthly to avoid the decomposition of carbonyls.

Mass Spectrometric Analysis

Liquid chromatography-mass spectrometry (LC-MS) was used in this study. Separation was done by an Agilent 1100 series LC, detection was done by a Thermo Fisher Scientific Linear Ion Trap Mass Spectrometer system (Thermo Fisher LTQ-XL). The LC separation was conducted with a Phenomenex Luna Omega 150 \times 2.1 mm 3 μ m Polar C18 column. All measurements were done by electrospray ionization in negative mode (ESI (-)). Detailed settings for the mass spectrometer and the HPLC can be found in Section S2 in Supplementary Information.

Iodometry UV-Vis Measurement

The solution and sample preparation procedure of iodometry can be found in Section S3, the method is adopted and modified based on the work of Mutzel et al.⁴⁴ UV-Vis instrument used in this experiment is Agilent 8453 UV/VIS spectrophotometer. Absorbance at 351 nm was selected to quantify the peroxide concentration in samples.

Safety

This project is associated with the use of 2,4-DNPH, concentrated acid, carcinogenic aldehydes, and a mass spectrometer. 2,4-DNPH is shock-sensitive and explosive when dried, hence it must be stored under damp conditions and away from oxidizer. Concentrated acid is required to make up the 2,4-DNPH derivatization solution, thus must be handled inside the fume hood, and appropriate personal protective equipment (PPE) should be used. Aldehydes involved, such as formaldehyde, are very volatile, therefore handling inside the fume hood with appropriate PPE required. The mass spectrometer is utilizing high voltage and high temperature at the injection housing. Therefore it is crucial to avoid touching the area during instrumental operations.

Results and Discussion

Carbonyl Production from Aging

Various carbonyls were recognized in all glycol samples. Different chromatograms of TEG and EJ were observed in Figures 1A and 1B after exposure to the air over weeks. Identities of detected peaks were confirmed via molecular mass, or spiking with pure carbonyl standards. Aldehydes and ketones with the same molecular mass were identified via MS² scan since their hydrazones have unique fragmentation profiles. The peak with m/z 163 is the indicator of aldehydes due to the loss of -RNO₂, while this fragment is absent in ketone-derived hydrazones.⁶⁰

Aged glycols contain carbonyls of various sizes. Small carbonyls, like formaldehyde or glycolaldehyde, were likely produced due to the decomposition of long-chain glycols; Large carbonyls, such as TEG-aldehyde ([2-(2-Hydroxyethoxy) ethoxy] acetaldehyde), PG-ketone (Lactaldehyde), or VG-ketone (Hydroxyacetone), were formed due to functionalizations which convert hydroxyl groups to the carbonyl groups. These functionalized carbonyls are

glycol-specific, as their structures are dependent on the parent glycol. In the TEG sample shown in Figure 1A, we identified the dominant carbonyl as TEG-aldehyde, which comes from the oxidation of one hydroxyl terminal on the glycol. Formaldehyde and glycolaldehyde were identified as the decomposition product of TEG, whose peaks were intensified after 7-8 weeks of storage. This indicates a rapid fragmentation of TEG has happened during its aging. The aged TEG also produced a peak of DEG-aldehyde, suggesting that DEG-aldehyde is one of the fragmentation products of the TEG molecule, this implies the gradual chain reduction of long glycols produces smaller derivatives.

EJ sample is based on a mixture of PG and VG, it contains PG and VG-derived carbonyls after aging, such as VG-aldehyde, PG-aldehyde, and ketones, as shown in Figure 1B. The aging of EJ has also intensified peaks of formaldehyde and glycolaldehyde, similar to the TEG sample. This suggests that these two carbonyls are the common products of glycol decomposition despite the structural differences. It is intriguing to note that the majority of identified carbonyl species were already present in samples before we started the experiment. Hence the accumulation of carbonyls was initiated while the product is still with the manufacturer or the vendor.

Carbonyl Accumulation in Pure Glycols

We selectively quantified formaldehyde and glycolaldehyde in all glycol samples involved in Experiment 1 (Figure 2), due to the limited commercial availability of pure carbonyl standards. Results in Figure 2 confirm that air-exposed glycols have a higher aldehyde concentration than sealed samples after 6 to 8 weeks of aging. When compared to the sealed sample, an air-exposed glycol usually has a higher final concentration of carbonyls while initial concentrations were similar. Hence, air exposure is a key factor of carbonyl formation during storage, which is also in agreement with the conditions required for autoxidation.

TEG samples under both aging conditions have by far the highest initial concentration of aldehydes, followed by EJ samples, while PG and DEG samples have the lowest. The

initial concentration of aldehydes is likely produced during manufacturing and transportation. Details of the initial and final carbonyl concentrations are listed in the Supplementary Information (Section S4). Among air-exposed samples, PG has the most rapid relative increase of formaldehyde, followed by TEG, EJ, VG, and DEG. However, TEG had the most rapid formation of absolute formaldehyde, as well as glycolaldehyde. Among sealed samples, the formation of carbonyls is not as rapid as air-exposed samples, but TEG and EJ still have a relatively more rapid formation than others. We noted that sealed samples are more representative of real-life storage of glycol-containing products, as the majority of the time closed.

An out-of-scale aldehyde concentration observed in TEG in Figure 2 indicates that TEG could undergo autoxidation more rapidly than others. It is likely due to chain lengths and the ether-link structure. The initiation of autoxidation is often carried out via electrophilic H-abstraction, which prefers carbon atoms adjacent to an electron-donating group.⁶¹ While hydroxyl groups are electron-donating, electron density on the ether group is higher (Kwok 1995). Hence, TEG is susceptible to H-abstraction by having two ether groups within the molecule. Additionally, a longer and less-hindered chain of TEG makes more active sites for H-abstraction. This allows more frequent 1,5-H shift, which is a key process of the peroxide formation and autoxidation propagation.^{32,62,63} Moreover, functionalized products such as TEG-aldehyde or DEG-aldehyde still retain multiple active sites for electrophilic addition. Hence subsequent autoxidation is likely to happen on those products, leading to a high yield of small carbonyls per glycol molecule. On the other hand, the chain length for PG, VG, and DEG are short, therefore fewer active carbons. Additional branching may also hinder efficient 1,5-H shifts.

Aging of TEG in Water Mixtures

Given that carbonyl formation was observed to be the most rapid in TEG, TEG was further used here for an in-depth investigation. To test out the effect of the water mixing ratio

on formation rates of formaldehyde and glycolaldehyde from TEG, we have monitored the concentration of the carbonyls in a gradient of water mixing ratio ranging from 0% to 70% water.

Quality Control

Two aspects in our experimental design may cause bias to our results and hence were investigated first. The first aspect is the evaporation of the solution, which concentrates analytes over time. This is due to uncovered air samples experiencing unavoidable solution evaporation constantly. According to the database,⁶⁴ all glycols in this work have far less vapor pressure (at least three orders of magnitude) than water. Therefore, we assume that loss of water contributed to all observed evaporations. This aspect was addressed by monitoring the mass loss of the solution in glycol-water mixtures over weeks. A first-order fitting of the remaining mass was performed for each of the four glycol-water mixing ratios. Based on this time-dependent trace of evaporation, a correction was applied to all of our observations.

Another aspect is the uneven recovery ratios of carbonyls from different glycol-water mixing ratios, especially when the ratio is affected by water evaporation. Although the method of standard addition was applied, which ideally eliminates all matrix effects, smaller recovery rates in pure glycol samples were observed. This is confirmed via four sets of repeated spike-recovery experiments. On average, we observed a 70.6% ($\pm 4.7\%$) recovery in pure glycol samples and 90.9% ($\pm 4.4\%$) in 50% glycol samples. Thus, we assumed a linear relationship between the recovery rates and glycol mixing ratios and applied the corresponding correction to all of our data. Details of bias correction to our data can be found in Section S5 in the Supplementary Information.

The mean error of standard addition in these replicates was determined. A total number of 16 standard addition (done on different days) was performed in this recovery experiment. The mean error of standard addition was calculated to be 7.45%, which will be treated as the standard error of all later carbonyl quantitation.

Effect of Water Mixing Ratios

The formation rate of carbonyls varies between different water mixing ratios for both formaldehyde (Figure 3A) and glycolaldehyde (Figure 3B). All data shown were corrected by the solvent evaporation and recovery artifacts, explained in the previous section. Both aldehydes exhibit a similar trend: the 50% mixing ratio was the fastest, followed by the 30% mixing ratio, and 0%, 10%, and 70% ratios have slower rates. We also noticed that the 50% mixing ratio has a two-stage time profile and that the formation rate was accelerated around day 20 in both aldehydes. This two-stage profile may have implications for the formation of peroxides in the mixture, which is a determining factor of carbonyl formation rates. This will be discussed in the latter section.

Rather, the 70% water sample displayed behavior that was inconsistent with other ratios. In terms of formaldehyde, its formation rate was comparable to pure and 10% water samples, while it started accelerating after day 30. Eventually, the final concentration of formaldehyde in the 70% mixing ratio was about 500% of the initial value, which is lower than the 30% and 50% mixing ratios (about 650% and 800%, respectively). In terms of glycolaldehyde, the time profile is almost overlapping with the pure sample. Overall, our results show that water likely plays a non-linear role in the autoxidation of TEG and the formation of carbonyls. Up to 50% water, the formation rate of carbonyls increased with the water mixing ratio; however, this trend is no longer observed at water ratios above that. The inconsistent behavior of a 70% mixing ratio requires further investigation.

Aging of 50% TEG

As we discussed in the previous section, 50% TEG has the most rapid carbonyl formation. Additionally, our previous work has observed that formaldehyde accumulation in the artificial fog juice (typically around 50% water) was more pronounced than in pure glycol done in this project.³⁸ As a result, we have conducted a separate experiment to further investigate the aging of 50% TEG in both air-exposed and sealed conditions.

According to Figure 4, air-exposed 50% TEG has a more rapid formation of both compounds than the air-exposed pure TEG, confirming that water is promoting the formation of carbonyls. As also mentioned previously, formaldehyde formation in the air-exposed 50% TEG sample appears to have two distinct stages before and after approximately day 22, where the formation rate of formaldehyde has drastically increased, indicating accelerated autoxidation. The final concentration of formaldehyde in air-exposed 50% TEG was about 400% of that in the pure sample, whereas for glycolaldehyde it was about 300%. The two-stage profile of formaldehyde has coincided with the evaporation of water. As we tracked the first-order rate of water evaporation from 50% TEG, we calculated that water would be mostly evaporated by day 22. Therefore, the presence or absence of water could potentially alter the formation of autoxidation products.

Iodometry and Peroxide Accumulation

Observations from the previous sections highlighted that the formation of aldehydes was not monotonic throughout the aging period. The rate of autoxidation was likely varying over time, and as such, it is crucial to monitor the peroxide concentration in glycol samples so that we can estimate the extent of autoxidation during air exposure.

The concentration of peroxides in air-exposed 50% TEG and other glycols were quantified at two stages of the experiment, as in Figure 5A. Overall, we observed all samples had higher peroxide concentrations at the end of the experiment. 50% TEG has the most rapid peroxide formation, which raised from about 1.4 mM to 7 mM. PG and VG have about 10 μ M and 35 μ M at the end, while their initial concentration was below LOD (3 μ M). DEG has an initial concentration of 14 μ M, which increased to 29 μ M eventually. The formation of peroxides mirrored that of carbonyls, and this was particularly pronounced for 50% TEG.

Figure 5B presents the average concentration of peroxides in a set of triplicate air-exposed 50% TEG samples throughout the experiment. Error bars on the peroxide concentration reflect the standard deviation of peroxide concentration in these samples. The two shaded

areas are the average formation rates of formaldehyde and glycolaldehyde in these samples with a three-point smoothing applied. The formation rate is calculated based on the slope of two consecutive points of their concentration profiles, i.e., the differential.

The peroxide concentration varied significantly as the exposure time got longer. Initially, it was less than 2000 μM in all triplicate samples, while a week later it started rising rapidly. Between day 22 and day 30, peroxide concentration reached a peak beyond 7000 μM . Finally, it starts gradually descending from the peak and is still above 6000 μM before we stopped measuring. The time profile of the carbonyl formation rate has shown a strong correlation with the peroxide concentration with the two reaching their peaks around the same time. This peak time also coincides with the time that water has completely evaporated. After the peak period, the carbonyl formation rate stabilized at around 300 μM per day.

The agreement between the peroxide and the carbonyl formation is a critical observation, indicating that the rapid carbonyl formation is the result of a high peroxide concentration. The involvement of water in autoxidation has never been investigated previously. The role of water could be very complicated and cannot be explicitly explained by our work; however, there are a few potential explanations. Water could increase the OH radical reactivity by changing the solution viscosity. Lower viscosity allows the diffusion of atmospheric OH radical towards the glycol, or diffusion of glycol molecules to the surface of the solution so direct contact with atmospheric oxidants is made.⁶⁵ OH radicals can also form a relatively stable solvation complex with a neighboring water molecule, thus the radical becomes more stable in the aqueous environment.⁶⁶ According to the literature value,⁶⁷ the viscosity of pure TEG is about 36 times higher than that of pure water.

Moreover, the presence of water can promote local OH formation in the solution. Indoor concentration of OH radicals are a few orders of magnitude lower than outdoors (about 10-6 ppb) due to the low availability of ultraviolet radiation,^{68,69} and their transportation from outdoors is less significant due to their reactive nature.⁷⁰ However, the transportation of ozone is more significant, whose indoor concentration is about 5-6 orders of magnitude higher

than the OH radical.^{71,72} Ozone, once dissolved in water, can spontaneously react with water to produce OH radicals.^{73,74} This reaction is favored in neutral or basic conditions since it is initiated by ozone and hydroxide ions, while the pH of fresh TEG is approximately 7.³⁶

Effect of Antioxidants

Compared to samples without antioxidants, Vitamin C has successfully suppressed the formation of both formaldehyde (Figure 6A) and glycolaldehyde (Figure 6B) in our sample throughout the entire period. For glycolaldehyde, the concentrations in the air-exposed sample were even smaller than those in the sealed sample, indicating that the anti-oxidizing capacity of Vitamin C overcame the enhanced oxidant exposure in the air-exposed sample. The suppression of formaldehyde formation by Vitamin C is likely due to its ability to scavenge a wide variety of reactive oxygen species,⁷⁵ including organic peroxides.⁷⁶ We could not apply iodometry after vitamin C application, as it can react with I_2 spontaneously and no I_3^- will be formed.⁷⁷

Conclusions

This study represents hitherto the most detailed investigation of autoxidation of common glycol species used in daily inhalable products, intending to understand toxic compound formation during storage. All of the investigated glycols exhibited the formation of harmful carbonyl compounds, including formaldehyde, and glycolaldehyde, among many others, when exposed to room air over weeks. The detection of such carbonyls also suggests the potential cause of various glycol-related health issues, such as EVALI, or voice loss experienced by stage actors. Our observations provide strong and novel evidence that autoxidation is responsible for their formation because 1) faster formation rates were observed for air-exposed samples, 2) TEG (with the longest chain) exhibited the most significant carbonyl formation, 3) peroxide formation corresponded with the carbonyl formation, and 4) the addition of an antioxidant

(L-ascorbic acid) suppressed carbonyl formation.

The formation of carbonyls in inhalable products can be a significant health concern. Formaldehyde and glycolaldehyde are known carcinogens, while peroxides belong to reactive oxygen species and introduce oxidative stress to the human body. Inhaling contaminated products, such as e-cigarettes or artificial fog, can represent an unrecognized exposure pathway to these harmful compounds. The actual exposure risk depends on the type of products used, their shelf age, as well as the indoor environment. For instance, smoking an e-cigarette could lead to high glycolaldehyde exposure despite only glycols and nicotine being involved; our previous study also showed that the frequent use of a fog machine in a poorly ventilated venue might lead to a formaldehyde concentration greater than 150 ppb in the air.³⁸ It is expected that e-cigarette smokers and people who frequently use such products in an indoor setting, e.g., actors and workers in the entertainment industries, are at a greater risk.

A discovery made by this work is the relationship between the carbonyl formation rate and the TEG-water mixing ratio. We have shown that water likely promoted the autoxidation of TEG. The explicit reason was complicated and could not be identified by this work, but possible explanations were explored. The mixture of glycols and water is variable across consumable products. For example, personal care products and cosmetics are water-dominant; paints and fog juices usually contain around 50% of water; e-cigarettes and surface coatings typically contain minimal water. Additionally, the pure form of glycols is not completely immune from oxidative degradation either, as shown by a slower but consistent carbonyl formation observed in this work, as well as the fact that many purchased glycols contained certain concentrations of carbonyl and peroxides.

Overall, our study raises potential concerns regarding product safety for glycol-based consumables. Proper storage protocols and expiration dates should be mandated and regulated. Based on this work, a few suggestions can be made to mitigate the risk of glycol autoxidation. First, minimizing air exposure is important to prevent rapid autoxidation. Second, avoiding glycol-water mixture during storage can slow down the autoxidation process. For

instance, artificial fog juices can be sold as TEG or a mixture of glycols without water, and consumers should mix it with water before use. While this work was limited to TEG-water mixtures, future studies should be extended to the water mixtures of other glycol species. Third, as shown in this work, the addition of antioxidants can suppress autoxidation and the formation of harmful chemicals. However, the inhalation risks of antioxidants themselves should be carefully evaluated before application.

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References

- (1) Wood, E. C.; Knighton, W. B.; Fortner, E. C.; Herndon, S. C.; Onasch, T. B.; Franklin, J. P.; Worsnop, D. R.; Dallmann, T. R.; Gentner, D. R.; Goldstein, A. H.; Harley, R. A. Ethylene Glycol Emissions from On-road Vehicles. Environmental Science & Technology **2015**, 49, 3322–3329.
- (2) Knop, K.; Hoogenboom, R.; Fischer, D.; Schubert, U. Poly(ethylene glycol) in Drug Delivery: Pros and Cons as Well as Potential Alternatives. Angewandte Chemie International Edition **2010**, 49, 6288–6308.
- (3) Mortensen, A. Re-evaluation of glycerol (E 422) as a food additive. EFSA Journal **2017**, 15, e04720.

- (4) Liu, G.; Zhu, L.; Hong, J.; Liu, H. Technical, Economical, and Environmental Performance Assessment of an Improved Triethylene Glycol Dehydration Process for Shale Gas. ACS Omega **2022**, 7, 1861–1873.
- (5) Mostafazadeh, A. K.; Rahimpour, M. R.; Shariati, A. VaporLiquid Equilibria of Water + Triethylene Glycol (TEG) and Water + TEG + Toluene at 85 kPa. Journal of Chemical & Engineering Data **2009**, 54, 876–881.
- (6) Velzen, A. V.; Vermeeren, Y.; Riel, A. V.; Meulenbelt, J.; de Vries, I. Ingestion of smoke fluid: be aware of diethylene glycol. Clinical Toxicology **2013**, 51, 907–907.
- (7) Martuzevicius, D.; Prasauskas, T.; Setyan, A.; O’Connell, G.; Cahours, X.; Julien, R.; Colard, S. Characterization of the Spatial and Temporal Dispersion Differences Between Exhaled E-Cigarette Mist and Cigarette Smoke. Nicotine Tob Res **2019**, 21, 1371–1377.
- (8) Zhao, T.; Nguyen, C.; Lin, C.-H.; Middlekauff, H. R.; Peters, K.; Moheimani, R.; Guo, Q.; Zhu, Y. Characteristics of secondhand electronic cigarette aerosols from active human use. Aerosol Science and Technology **2017**, 51, 1368–1376.
- (9) Woodall, M.; Jacob, J.; Kalsi, K. K.; Schroeder, V.; Davis, E.; Kenyon, B.; Khan, I.; Garnett, J. P.; Tarran, R.; Baines, D. L. E-cigarette constituents propylene glycol and vegetable glycerin decrease glucose uptake and its metabolism in airway epithelial cells in vitro. Am J Physiol Lung Cell Mol Physiol **2020**, 319, L957–L967.
- (10) Flora, J. W.; Meruva, N.; Huang, C. B.; Wilkinson, C. T.; Ballentine, R.; Smith, D. C.; Werley, M. S.; McKinney, W. J. Characterization of potential impurities and degradation products in electronic cigarette formulations and aerosols. Regulatory Toxicology and Pharmacology **2016**, 74, 1–11.
- (11) Fabius, R.; Phares, S. Companies That Promote a Culture of Health, Safety, and Wellbeing Outperform in the Marketplace. Journal of Occupational & Environmental Medicine **2021**, 63, 456–461.

- (12) Isen, A.; Rossin-Slater, M.; Walker, W. R. Every Breath You Take—Every Dollar You’ll Make: The Long-Term Consequences of the Clean Air Act of 1970. Journal of Political Economy **2017**, 125, 848–902.
- (13) Jerzynski, T.; Stimson, G. V.; Shapiro, H.; Król, G. Estimation of the global number of e-cigarette users in 2020. Harm Reduct J **2021**, 18, 109.
- (14) Teschke, K.; Chow, Y.; Brauer, M.; van Netten, C.; Varughese, S.; Kennedy, S. Atmospheric effects in the entertainment industry: constituents, exposures and health effects. UBC Faculty Research and Publications **2003**,
- (15) Varughese, S.; Teschke, K.; Brauer, M.; Chow, Y.; van Netten, C.; Kennedy, S. M. Effects of theatrical smokes and fogs on respiratory health in the entertainment industry. Am J Ind Med **2005**, 47, 411–418.
- (16) Wieslander, G.; ck, D.; Lindgren, T. Experimental exposure to propylene glycol mist in aviation emergency training: acute ocular and respiratory effects. Occup Environ Med **2001**, 58, 649–655.
- (17) Baker, M. M.; Procter, T. D.; Belzak, L.; Ogunnaike-Cooke, S. Vaping-associated lung illness (VALI) in Canada: a descriptive analysis of VALI cases reported from September 2019 to December 2020. Health Promot Chronic Dis Prev Can **2022**, 42, 37–44.
- (18) O’Callaghan, M.; Boyle, N.; Fabre, A.; Keane, M. P.; McCarthy, C. Vaping-Associated Lung Injury: A Review. Medicina (Kaunas) **2022**, 58.
- (19) Ogunwale, M. A.; Li, M.; Ramakrishnam Raju, M. V.; Chen, Y.; Nantz, M. H.; Conklin, D. J.; Fu, X. A. Aldehyde Detection in Electronic Cigarette Aerosols. ACS Omega **2017**, 2, 1207–1214.
- (20) Klager, S.; Vallarino, J.; MacNaughton, P.; Christiani, D. C.; Lu, Q.; Allen, J. G.

Flavoring Chemicals and Aldehydes in E-Cigarette Emissions. Environmental Science & Technology **2017**, 51, 10806–10813.

(21) Geiss, O.; Bianchi, I.; Barrero-Moreno, J. Correlation of volatile carbonyl yields emitted by e-cigarettes with the temperature of the heating coil and the perceived sensorial quality of the generated vapours. International Journal of Hygiene and Environmental Health **2016**, 219, 268–277.

(22) Chen, W.; Wang, P.; Ito, K.; Fowles, J.; Shusterman, D.; Jaques, P. A.; Kumagai, K. Measurement of heating coil temperature for e-cigarettes with a "top-coil" clearomizer. PLoS One **2018**, 13, e0195925.

(23) Lau, C.; Zhao, R.; Vethanayagam, D. Chemistry Review of Vaping Products and Respiratory Injury. Spectrum **2020**,

(24) Turan-Ertas, T.; Gurol, M. D. Oxidation of diethylene glycol with ozone and modified Fenton processes. Chemosphere **2002**, 47, 293–301.

(25) Mantzavinos, D.; Livingston, A. G.; Hellenbrand, R.; Metcalfe, I. S. Wet air oxidation of polyethylene glycols mechanisms, intermediates and implications for integrated chemical-biological wastewater treatment. Chemical Engineering Science **1996**, 51, 4219–4235.

(26) Lloyd, W. G. The Low Temperature Autoxidation of Diethylene Glycol1. Journal of the American Chemical Society **1956**, 78, 72–75.

(27) Bianchi, F. et al. Highly Oxygenated Organic Molecules (HOM) from Gas-Phase Autoxidation Involving Peroxy Radicals: A Key Contributor to Atmospheric Aerosol. Chemical Reviews **2019**, 119, 3472–3509.

(28) Taghvaei, M.; Jafari, S. M. Application and stability of natural antioxidants in edible

oils in order to substitute synthetic additives. Journal of Food Science and Technology **2013**, 52, 1272–1282.

(29) Wang, S.; Takhar, M.; Zhao, Y.; Al Rashdi, L. N. S.; Chan, A. W. H. Dynamic Oxidative Potential of Organic Aerosol from Heated Cooking Oil. ACS Earth and Space Chemistry **2021**, 5, 1150–1162.

(30) Sun, Y.-E.; Wang, W.-D.; Chen, H.-W.; Li, C. Autoxidation of Unsaturated Lipids in Food Emulsion. Critical Reviews in Food Science and Nutrition **2011**, 51, 453–466.

(31) Prabhu, H. R. Lipid peroxidation in culinary oils subjected to thermal stress. Indian Journal of Clinical Biochemistry **2000**, 15, 1–5.

(32) Crounse, J. D.; Nielsen, L. B.; Jørgensen, S.; Kjaergaard, H. G.; Wennberg, P. O. Autoxidation of Organic Compounds in the Atmosphere. The Journal of Physical Chemistry Letters **2013**, 4, 3513–3520.

(33) Zhao, Y.; Thornton, J. A.; Pye, H. O. T. Quantitative constraints on autoxidation and dimer formation from direct probing of monoterpene-derived peroxy radical chemistry. Proceedings of the National Academy of Sciences **2018**, 115, 12142–12147.

(34) Benoit, R.; Belhadj, N.; Lailliau, M.; Dagaut, P. Autoxidation of terpenes, a common pathway in tropospheric and low temperature combustion conditions: the case of limonene and α -pinene. Atmospheric Chemistry and Physics Discussions **2021**, 2021, 1–21.

(35) Iyer, S.; Rissanen, M. P.; Valiev, R.; Barua, S.; Krechmer, J. E.; Thornton, J.; Ehn, M.; Kurtén, T. Molecular mechanism for rapid autoxidation in α -pinene ozonolysis. Nature Communications **2021**, 12.

(36) Trueba, L.; Gaston, T.; Brackin, J.; Miller, J.; You, B.-H. Effective strategies to re-

duce triethylene glycol consumption in natural gas processing plants. Case Studies in Chemical and Environmental Engineering **2022**, 5, 100196.

(37) Simic, M. G. Free radical mechanisms in autoxidation processes. Journal of Chemical Education **1981**, 58, 125.

(38) Guo, X.; Ehindero, T.; Lau, C.; Zhao, R. Impact of glycol-based solvents on indoor air quality—Artificial fog and exposure pathways of formaldehyde and various carbonyls. Indoor Air **2022**, 32, e13100.

(39) Destailats, H.; Lunden, M. M.; Singer, B. C.; Coleman, B. K.; Hodgson, A. T.; Weschler, C. J.; Nazaroff, W. W. Indoor Secondary Pollutants from Household Product Emissions in the Presence of Ozone: A Bench-Scale Chamber Study. Environmental Science & Technology **2006**, 40, 4421–4428.

(40) Abdollahi, M.; Hosseini, A. Encyclopedia of Toxicology; Elsevier, 2014; pp 653–656.

(41) Debra A. Kaden, G. D. N. P. W., Corinne Mandin WHO Guidelines for Indoor Air Quality: Selected Pollutants; WHO Guidelines Approved by the Guidelines Review Committee; World Health Organization, 2010; pp 103–156.

(42) Robert, B.; Nallathambi, G. Indoor formaldehyde removal by catalytic oxidation, adsorption and nanofibrous membranes: a review. Environmental Chemistry Letters **2021**, 19, 2551–2579.

(43) Hajizadeh, Y.; Teiri, H.; Pourzamzni, H. Phytoremediation of formaldehyde from indoor environment by ornamental plants: An approach to promote occupants health. International Journal of Preventive Medicine **2018**, 9, 70.

(44) Mutzel, A.; Poulain, L.; Berndt, T.; Iinuma, Y.; Rodigast, M.; Böge, O.; Richters, S.; Spindler, G.; Sipilä, M.; Jokinen, T.; Kulmala, M.; Herrmann, H. Highly Oxidized

Multifunctional Organic Compounds Observed in Tropospheric Particles: A Field and Laboratory Study. Environmental Science & Technology **2015**, 49, 7754–7761.

(45) Zhang, X.; McVay, R. C.; Huang, D. D.; Dalleska, N. F.; Aumont, B.; Flagan, R. C.; Seinfeld, J. H. Formation and evolution of molecular products in α -pinene secondary organic aerosol. Proceedings of the National Academy of Sciences **2015**, 112, 14168–14173.

(46) Zhang, X. et al. Highly Oxygenated Multifunctional Compounds in α -Pinene Secondary Organic Aerosol. Environmental Science & Technology **2017**, 51, 5932–5940.

(47) Zhou, S.; Rivera-Rios, J. C.; Keutsch, F. N.; Abbatt, J. P. D. Identification of organic hydroperoxides and peroxy acids using atmospheric pressure chemical ionization–tandem mass spectrometry (APCI-MS/MS): application to secondary organic aerosol. Atmospheric Measurement Techniques **2018**, 11, 3081–3089.

(48) Zhang, N.; Li, Y.; Wen, S.; Sun, Y.; Chen, J.; Gao, Y.; Sagymbek, A.; Yu, X. Analytical methods for determining the peroxide value of edible oils: A mini-review. Food Chemistry **2021**, 358, 129834.

(49) Zhao, R.; Kenseth, C. M.; Huang, Y.; Dalleska, N. F.; Seinfeld, J. H. Iodometry-Assisted Liquid Chromatography Electrospray Ionization Mass Spectrometry for Analysis of Organic Peroxides: An Application to Atmospheric Secondary Organic Aerosol. Environmental Science & Technology **2018**, 52, 2108–2117.

(50) Mertes, P.; Pfaffenberger, L.; Dommen, J.; Kalberer, M.; Baltensperger, U. Development of a sensitive long path absorption photometer to quantify peroxides in aerosol particles (Peroxide-LOPAP). Atmospheric Measurement Techniques **2012**, 5, 2339–2348.

(51) Gautam, T.; Wu, S.; Ma, J.; Zhao, R. Potential Matrix Effects in Iodometry Determination of Peroxides in Aerosol Particles.

nation of Peroxides Induced by Olefins. The Journal of Physical Chemistry A **2022**,
126, 2632–2644.

(52) Piazzon, A.; Forte, M.; Nardini, M. Characterization of Phenolics Content and Antioxidant Activity of Different Beer Types. Journal of Agricultural and Food Chemistry **2010**, 58, 10677–10683.

(53) Hah, Y.-S.; Chung, H. J.; Sontakke, S. B.; Chung, I.-Y.; Ju, S.; Seo, S.-W.; Yoo, J.-M.; Kim, S.-J. Ascorbic acid concentrations in aqueous humor after systemic vitamin C supplementation in patients with cataract: pilot study. BMC Ophthalmology **2017**, 17.

(54) Kim, D.-O.; Lee, K. W.; Lee, H. J.; Lee, C. Y. Vitamin C Equivalent Antioxidant Capacity (VCEAC) of Phenolic Phytochemicals. Journal of Agricultural and Food Chemistry **2002**, 50, 3713–3717.

(55) Ma, Y.; Zhang, Y.; Gao, J.; Ouyang, H.; He, Y.; Fu, Z. PEGylated Ni Single-Atom Catalysts as Ultrasensitive Electrochemiluminescent Probes with Favorable Aqueous Dispersibility for Assaying Drug-Resistant Pathogens. Analytical Chemistry **2022**, 94, 14047–14053.

(56) Bracher, A.; Doran, S. F.; Squadrito, G. L.; Postlethwait, E. M.; Bowen, L.; Matalon, S. Targeted Aerosolized Delivery of Ascorbate in the Lungs of Chlorine-Exposed Rats. Journal of Aerosol Medicine and Pulmonary Drug Delivery **2012**, 25, 333–341.

(57) Jiao, J.; Meng, N.; Wang, H.; Zhang, L. The effects of vitamins C and B12 on human nasal ciliary beat frequency. BMC Complementary and Alternative Medicine **2013**, 13.

(58) Brady, O. L.; Elsmie, G. V. The use of 2:4-dinitrophenylhydrazine as a reagent for aldehydes and ketones. Analyst **1926**, 51, 77–78.

- (59) Plater, M. J. Shaken, not stirred: a schools test for aldehydes and ketones. Journal of Chemical Research **2019**, 44, 104–107.
- (60) de M. Ochs, S.; Fasciotti, M.; Netto, A. D. P. Analysis of 31 Hydrazones of Carbonyl Compounds by RRLC-UV and RRLC-MS(/MS): A Comparison of Methods. Journal of Spectroscopy **2015**, 2015, 1–11.
- (61) Moc, J.; Simmie, J. M. Hydrogen Abstraction from n-Butanol by the Hydroxyl Radical: High Level Ab Initio Study of the Relative Significance of Various Abstraction Channels and the Role of Weakly Bound Intermediates. The Journal of Physical Chemistry A **2010**, 114, 5558–5564.
- (62) Møller, K. H.; Bates, K. H.; Kjaergaard, H. G. The Importance of Peroxy Radical Hydrogen-Shift Reactions in Atmospheric Isoprene Oxidation. The Journal of Physical Chemistry A **2019**, 123, 920–932.
- (63) Mentel, T. F.; Springer, M.; Ehn, M.; Kleist, E.; Pullinen, I.; Kurtén, T.; Rissanen, M.; Wahner, A.; Wildt, J. Formation of highly oxidized multifunctional compounds: autoxidation of peroxy radicals formed in the ozonolysis of alkenes – deduced from structure–product relationships. Atmospheric Chemistry and Physics **2015**, 15, 6745–6765.
- (64) Kim, S.; Chen, J.; Cheng, T.; Gindulyte, A.; He, J.; He, S.; Li, Q.; Shoemaker, B. A.; Thiessen, P. A.; Yu, B.; Zaslavsky, L.; Zhang, J.; Bolton, E. E. PubChem 2023 update. Nucleic Acids Research **2022**, 51, D1373–D1380.
- (65) Price, H. C.; Murray, B. J.; Mattsson, J.; O'Sullivan, D.; Wilson, T. W.; Baustian, K. J.; Benning, L. G. Quantifying water diffusion in high-viscosity and glassy aqueous solutions using a Raman isotope tracer method. Atmospheric Chemistry and Physics **2014**, 14, 3817–3830.
- (66) Vassilev, P.; Louwerse, M. J.; Baerends, E. J. Hydroxyl Radical and Hydroxide Ion in

Liquid Water: A Comparative Electron Density Functional Theory Study. The Journal of Physical Chemistry B **2005**, 109, 23605–23610.

(67) Guo, Z.; Zhang, J.; Zhang, T.; Li, C.; Zhang, Y.; Bai, J. Liquid viscosities, excess properties, and viscous flow thermodynamics of triethylene glycolwater mixtures at T=(298.15, 303.15, 308.15, 313.15, and 318.15) K. Journal of Molecular Liquids **2012**, 165, 27–31.

(68) Weschler, C. J.; Shields, H. C. Production of the Hydroxyl Radical in Indoor Air. Environmental Science & Technology **1996**, 30, 3250–3258.

(69) Reidy, E. et al. Measurements of Hydroxyl Radical Concentrations during Indoor Cooking Events: Evidence of an Unmeasured Photolytic Source of Radicals. Environmental Science & Technology **2023**, 57, 896–908.

(70) Abbatt, J. P. D.; Wang, C. The atmospheric chemistry of indoor environments. Environmental Science: Processes & Impacts **2020**, 22, 25–48.

(71) Weschler, C. J. Ozone in Indoor Environments: Concentration and Chemistry. Indoor Air **2000**, 10, 269–288.

(72) Zhang, J.; Liou, P. J. Ozone in Residential Air: Concentrations, I/O Ratios, Indoor Chemistry, and Exposures. Indoor Air **1994**, 4, 95–105.

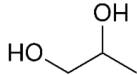
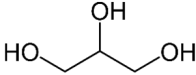
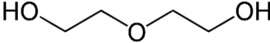
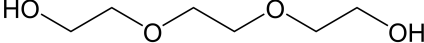
(73) Yasui, K.; Tuziuti, T.; Kanematsu, W. Mechanism of OH radical production from ozone bubbles in water after stopping cavitation. Ultrasonics Sonochemistry **2019**, 58, 104707.

(74) Wu, Z.; Abramova, A.; Nikonov, R.; Cravotto, G. Sonozonation (sonication/ozonation) for the degradation of organic contaminants – A review. Ultrasonics Sonochemistry **2020**, 68, 105195.

- (75) Njus, D.; Kelley, P. M.; Tu, Y.-J.; Schlegel, H. B. Ascorbic acid: The chemistry underlying its antioxidant properties. Free Radical Biology and Medicine **2020**, 159, 37–43.
- (76) Jenkins, K. F.; Hershberger, S. A.; Hershberger, J. W.; Marshall, R. Spontaneous stepwise reduction of an organic peroxide by ascorbic acid. The Journal of Organic Chemistry **1988**, 53, 3393–3395.
- (77) Silva, C. R.; Simoni, J. A.; Collins, C. H.; Volpe, P. L. O. Ascorbic Acid as a Standard for Iodometric Titrations. An Analytical Experiment for General Chemistry. Journal of Chemical Education **1999**, 76, 1421.

Tables

Table 1: Glycols of Interest in this Study

Name of Glycol	Common applications	Structure/composition
propylene glycol (PG)	Food & drug additives, E-Juice solvent	
Glycerol (VG)	Food & drug additives, E-Juice solvent	
Diethylene glycol (DEG)	Food & drug additive, Smallest poly-glycol	
Triethylene glycol (TEG)	Small poly-glycol, Solvent of Fog juice, common de-icer	
E-juice (EJ)	Basic version of any commercial E-juice	50% PG, 50% VG, 10 mg/ml Nicotine

689 **Figures**

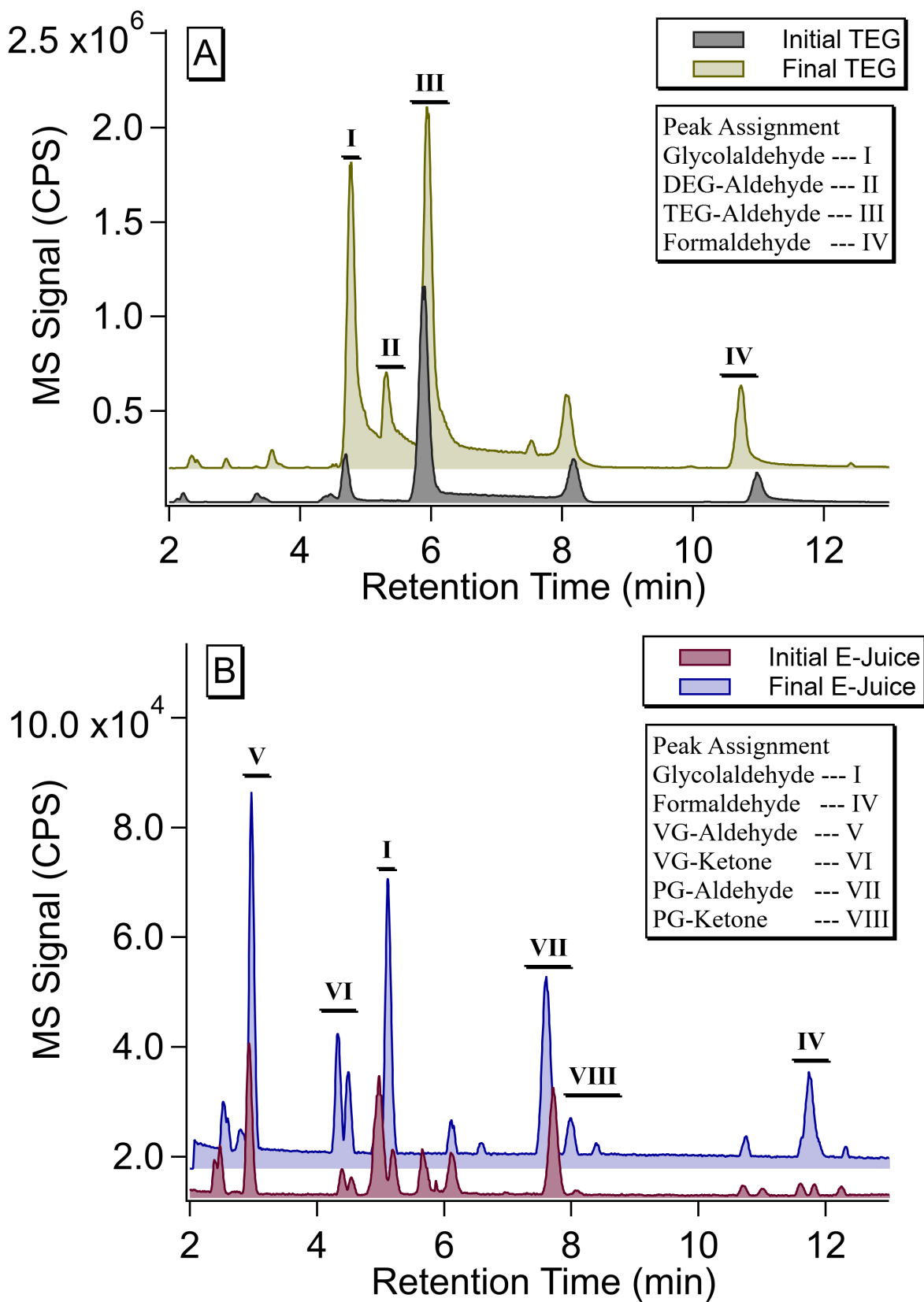


Figure 1: Base-peak chromatogram of all carbonyls detected in A) TEG samples and B) EJ samples the initial (week 1) and the final (week 8) stages of the aging experiment.

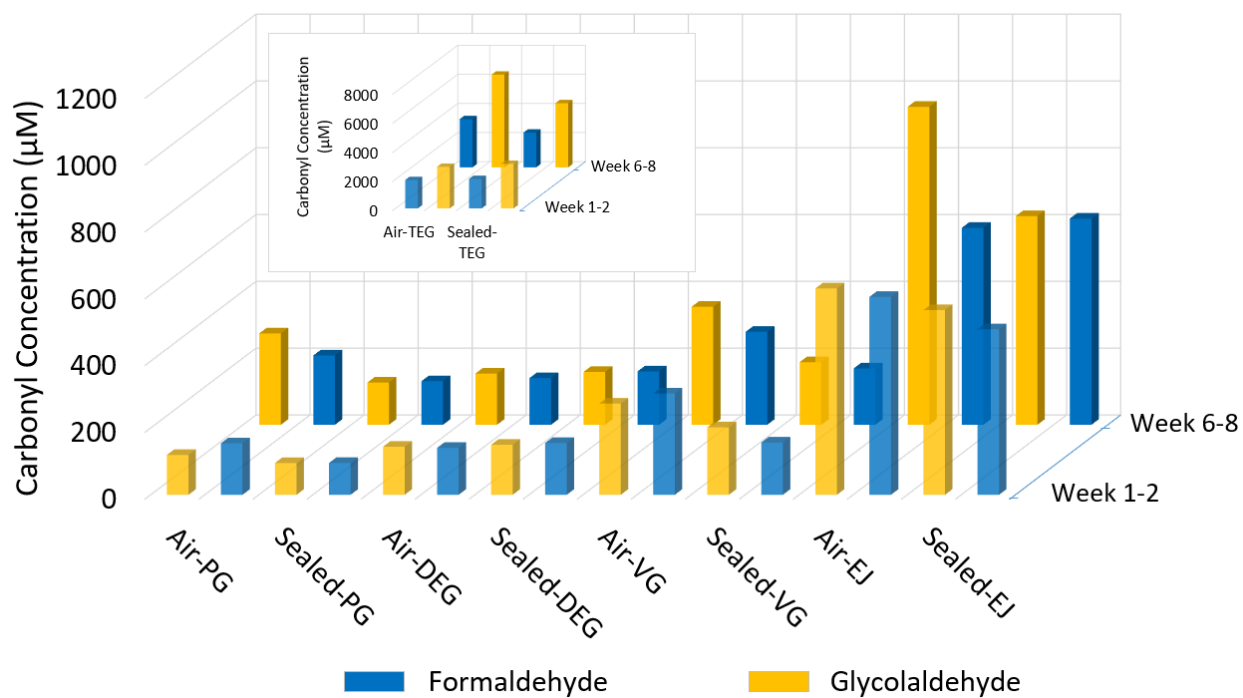


Figure 2: Quantitation of formaldehyde and glycolaldehyde in all glycol samples. The bars on the front are the 2-week average concentration at the beginning of the exposure; the Bars on the back are the 2-week average at the end of the experiment; The sub-window represents the result obtained from TEG samples.

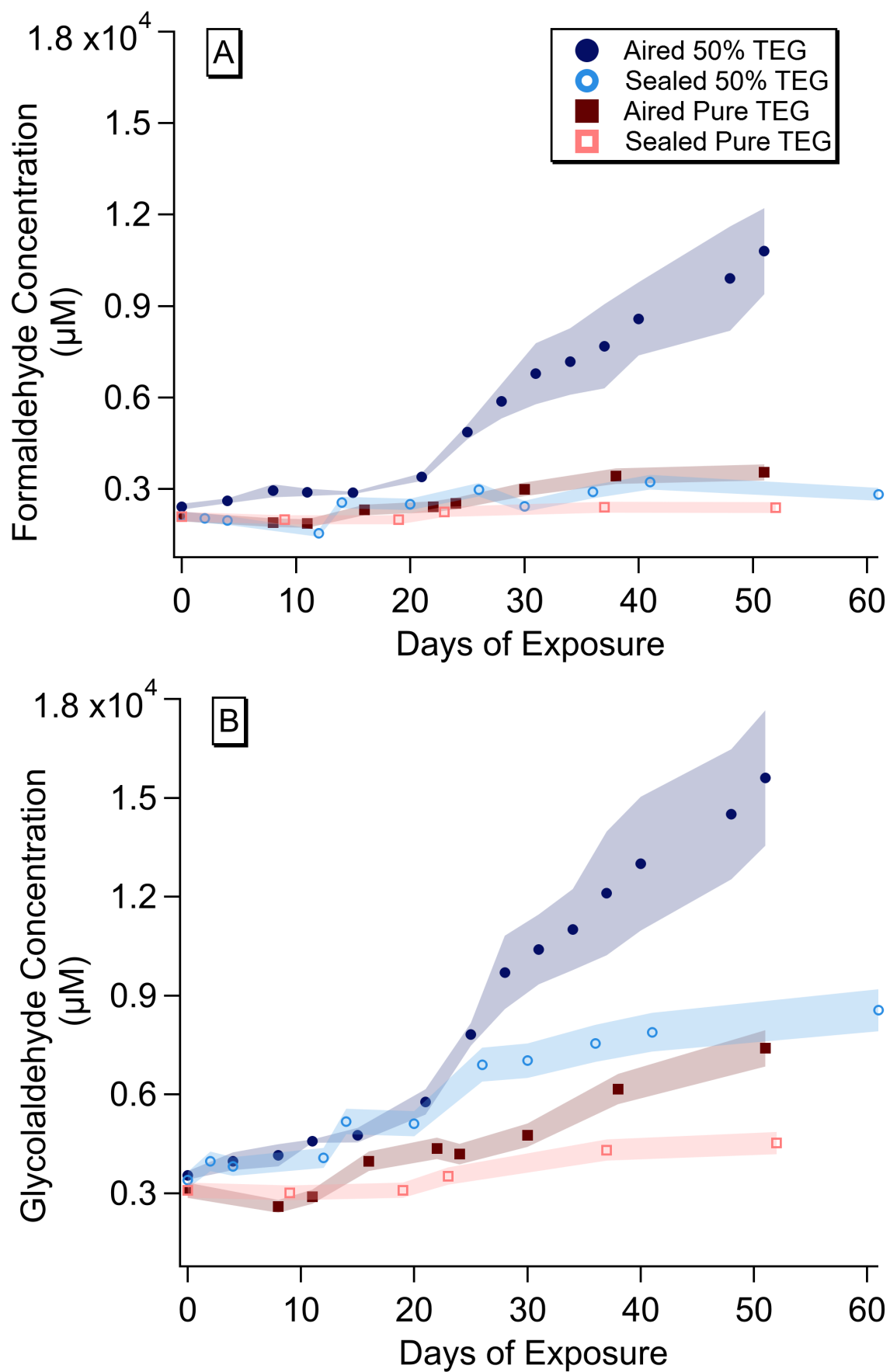


Figure 3: Formation of (A) formaldehyde and ³³ (B) glycolaldehyde in TEG under different water mixing ratios.

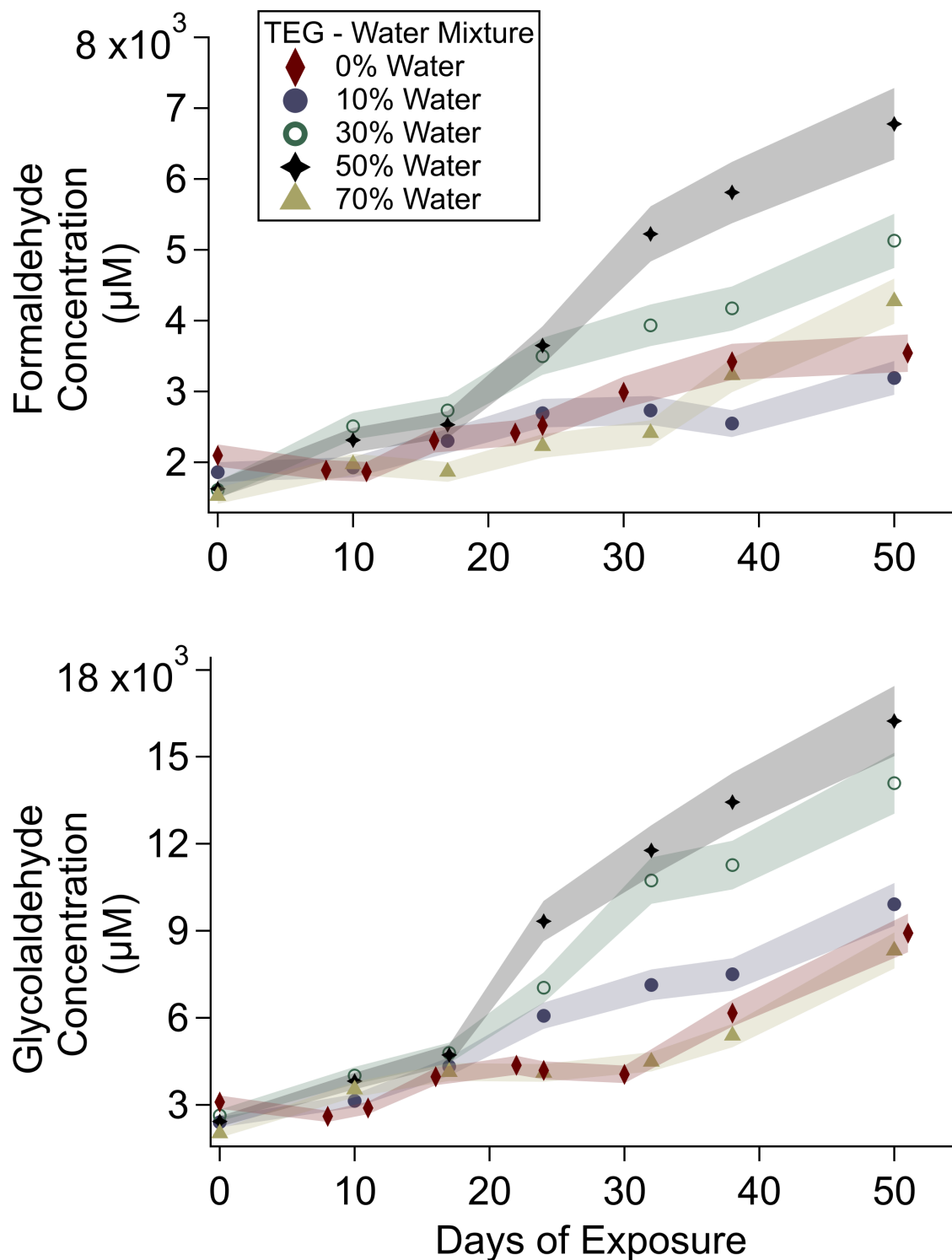


Figure 4: Formation of Carbonyls in 50% water-TEG mixture and pure TEG; A) Formation of formaldehyde; B) Formation of glycolaldehyde. The error band of air-exposed 50% represents the standard deviation determined from the triplet group, and the error bands of other samples are the mean error of standard addition (7.45%), determined previously in the quality control section.

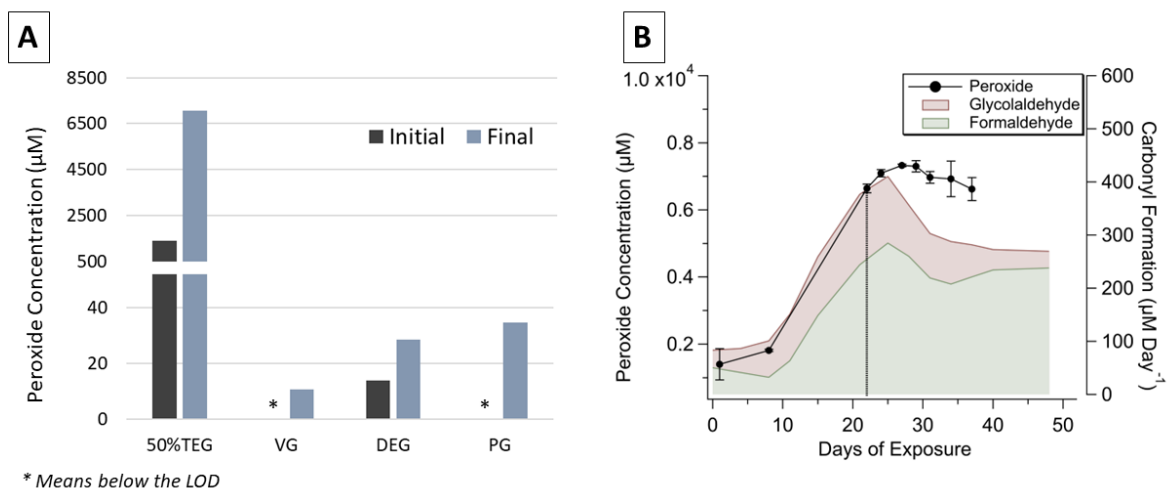


Figure 5: Summary of peroxide determination (A) peroxide concentration in air-exposed glycol sample at two different stages (B) time-dependent peroxide concentration and carbonyl formation rate in air-exposed 50% water TEG sample; the dashed line represents the day when more than 99% of water evaporation from the sample.

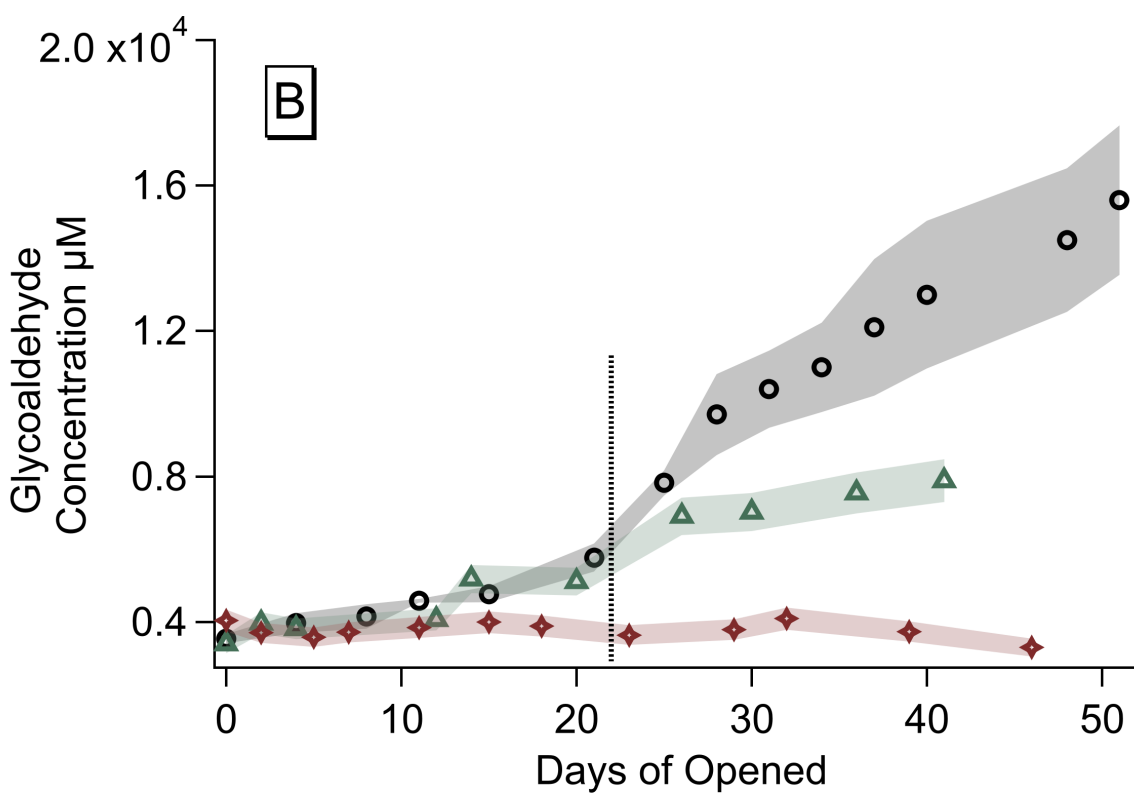
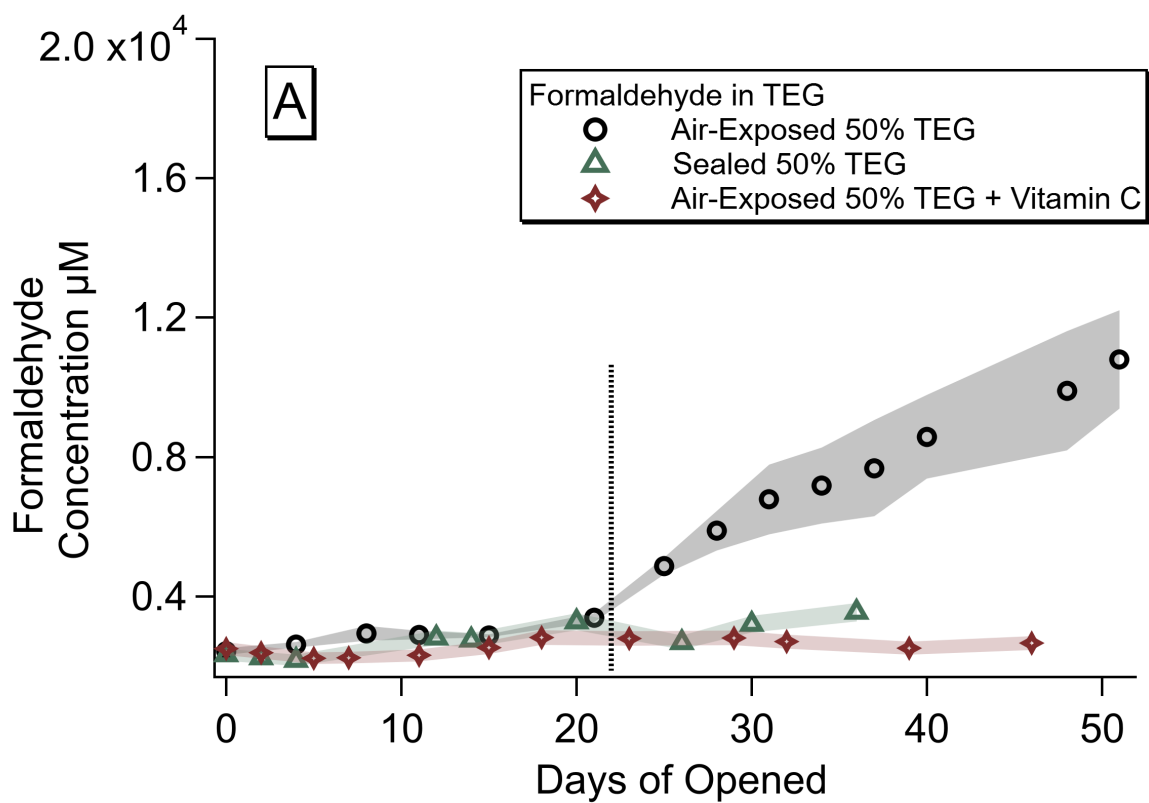


Figure 6: Formation of (A) formaldehyde and (B) glycoaldehyde in the air-exposed group, sealed group, and an antioxidant-added group of TEG samples; dashed lines represent 99% of water evaporated from the mixture.