

Liquid crystal display screens as a source for indoor volatile organic compounds

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Liquid crystal displays (LCDs) have profoundly shaped the lifestyle of humans. However, despite extensive use, their impacts on indoor air quality are unknown. Here, we perform flow cell experiments on three different LCDs, including a new computer monitor, a used laptop, and a new television, to investigate whether their screens can emit air constituents. We found that more than 30 volatile organic compounds (VOCs) were emitted from LCD screens, with a total screen area-normalized emission rate of up to $(8.25 \pm 0.90) \times 10^9$ molecules \cdot s⁻¹ \cdot cm⁻². In addition to VOCs, 10 liquid crystal monomers (LCMs), a commercial chemical widely used in LCDs, were also observed to be released from those LCD screens. The structural identification of VOCs is based on a “building block” hypothesis (i.e., the screen-emitted VOCs originate from the “building block chemicals” used in the manufacturing of liquid crystals), which are the key components of LCD screens. The identification of LCMs is based upon the detailed information of 362 currently produced LCMs. The emission rates of VOCs and LCMs increased by up to a factor of 9, with an increase of indoor air humidity from 23 to 58% due to water-organic interactions likely facilitating the diffusion rates of organics. These findings indicate that LCD screens are a potentially important source for indoor VOCs that has not been considered previously.

liquid crystal displays | indoor air quality | volatile organic compounds | commercial chemicals | liquid crystal monomers

Humans spend about 90% of their time indoors, where they are exposed to many indoor air constituents (1–3). Volatile organic compounds (VOCs) are a major class of indoor air constituents that have raised serious public concerns owing to their adverse health effects (4–6). Human exposure to indoor VOCs and related secondary organic aerosols can result in a wide range of negative health outcomes such as respiratory and heart diseases (7–9). In response to the health risks posed by these harmful chemicals, the World Health Organization has established indoor air quality management guidelines for VOCs such as formaldehyde and benzene (10). Consequently, identifying the sources of indoor VOCs and quantifying their emission rates is of critical importance for their corresponding health risk assessment and for the future development of indoor air quality control measures.

Indoors, VOCs are known to be emitted from a wide variety of sources. These sources include building materials (11), furnishings (12), household products (e.g., detergents) (13), personal care products (e.g., cosmetics) (14), and human activities (e.g., cooking) (15). In addition to these relatively well-studied sources, modern electronic devices that contain large numbers of commercial chemicals (16, 17) may also be a source for indoor VOCs. Liquid crystal displays (LCDs) are one such representative group of modern electronic devices. LCDs, such as computer monitors, laptops, and digital televisions (TVs), are widely used indoors and have become an important aspect of daily life (18). The global annual production of LCD panels in 2018 is 198 million m² and is expected to increase into the foreseeable future, with the increasing demand for convenient communication (19, 20). However, despite their global widespread use, the potential impact of LCDs on indoor air quality is unknown.

LCDs are typically designed with large colorful display screens. Recent studies found liquid crystal monomers (LCMs), a group of

synthetic organic chemicals extensively used in LCD screens with potential toxic effects on humans (21), were present in indoor dust (21, 22), indicating that LCMs could be released to the indoor environment during the utilization of LCDs. Given this, it is reasonable to assume that other chemicals within LCD screens may also be released to the surrounding air and become a component of indoor VOCs. We note that limited evidence exists on the VOC emissions during the manufacturing of LCD screens (23, 24). However, these few previous studies only focused on a small number of selected VOCs, such as toluene and xylene, utilizing a relatively slow time response, offline-targeted chemical analysis approach. More importantly, the information associated with the final LCD screen products (not the screens as they are being manufactured) is still lacking. Thus, it remains an open question whether LCD screens exert impacts on indoor VOCs.

Here, the potential for VOC emissions from LCD screens was investigated utilizing a flow cell system (*SI Appendix, Fig. S1*) combined with a Vocus proton transfer reaction mass spectrometry (PTR-TOFMS) (25). The use of the Vocus PTR-TOFMS allows high time resolution, online nontargeted measurements for VOCs. We found pronounced VOC emissions from three LCD screens (a new computer monitor, a used laptop, and a new TV screen; *SI Appendix, Table S1*), with emission rates increasing with increased relative humidity (RH). These results demonstrate that LCD screens represent a previously unrecognized source for indoor VOCs, which can inform future risk evaluation for these mass-produced consumer products.

Results and Discussion

Evidence of VOC and LCM Emissions from LCD Screens. The composition of genuine indoor air passing through either a flow cell placed

Significance

Liquid crystal displays (LCDs), ubiquitously used indoors in smartphones, computer monitors, laptops, and televisions, have become an essential aspect of modern life. We find LCD screens can emit significant levels of volatile organic compounds (VOCs), an important class of indoor air constituents with known adverse health effects. These screen-emitted VOCs are likely derived from the “building block chemicals” used in the manufacturing of liquid crystals. The results indicate that LCD screens are a previously unrecognized source for indoor VOCs, highlighting the need to better understand the environmental fate and toxicological properties associated with the air constituents emitted from LCD screens.

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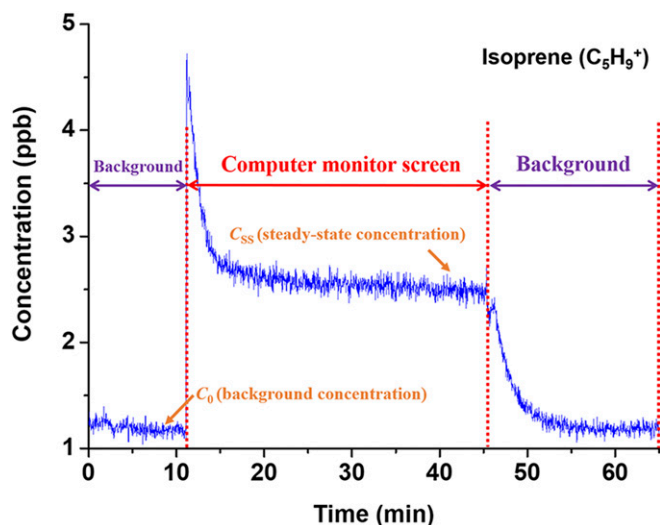


Fig. 1. Dynamic change of isoprene concentration (measured as $C_5H_9^+$ in the Vocus PTR-TOFMS) during a flow cell experiment. Experimental conditions are the following: computer monitor screen, genuine indoor air (in a laboratory at the University of Toronto), 296 K, and 58% RH. Experimental setup and procedure can be seen in *SI Appendix*, section S1 and Fig. S1.

on a clean glass plate (denoted background air) or another flow cell placed on an LCD screen (denoted screen air; *SI Appendix*, Fig. S1) was measured with a Vocus PTR-TOFMS. The LCD screen was turned off throughout the flow cell experiments. By comparing the levels of VOCs in screen air and those in background air, we can determine whether the investigated LCD screen can emit VOCs. For example, for a given VOC, if screen air possesses a higher concentration than background air (i.e., screen air > background air), this reflects a release of VOC from the LCD screen. Conversely, if there is no significant difference in the VOC concentration between screen air and background air (i.e., screen air = background air), this indicates little-to-no VOC emission from the screen. By using similar flow cells for the screen air and background air measurements, we can rule out that the source of VOC emissions is from flow cell components (e.g., O-ring elastomers). Additionally, placement of the flow cell on the screen (*SI Appendix*, Fig. S1) confirms that the LCD screen is the only VOC source and not, for example, its plastic housing. Here, we use the emission of isoprene as an example to illustrate the flow cell experimental results.

Fig. 1 shows the dynamic change of isoprene concentration (measured as $C_5H_9^+$ in the Vocus PTR-TOFMS; see *Structural Identification of LCMs and VOCs* for its identification) during a computer monitor screen experiment. The experiment consisted of three steps. Step 1 was a background period, which assessed the concentration of isoprene in background indoor air (1.2 ppb). In step 2, indoor air was introduced into a flow cell placed on a monitor screen (denoted screen flow cell). It was found that the isoprene concentration first increased and then decreased quickly until it reached a steady-state level (2.5 ppb). The initial increase is likely caused by an accumulation of isoprene inside the screen flow cell during the background measurement. Specifically, the screen flow cell was “isolated” from the ambient environment in step 1 (*SI Appendix*, section S1); when indoor air was flowing through the flow cell placed on a glass plate, the air is “stagnant” in the screen flow cell (*SI Appendix*, section S1). The monitor screen continually emitted isoprene during this period. As a result, isoprene accumulated in the screen flow cell, as in a headspace experiment. This accumulation effect may explain the observed initial increase of isoprene concentration in

Fig. 1. The isoprene concentration then dropped to a lower, steady-state level, reflecting that a balance was reached for the monitor screen–indoor air interactions. It should be noted that the steady-state concentration of isoprene (C_{ss} in Fig. 1) is 2.1 times higher than the background concentration (C_0 in Fig. 1), providing clear evidence for the emission of isoprene from the monitor screen. Finally, in step 3, isoprene concentration dropped to the background level when measuring the background indoor air again.

In addition to VOCs, the emission of LCMs, which generally have a biphenyl backbone structure (26), can also be observed. For example, the concentration of 1-(4-propylcyclohexyl)-4-vinylcyclohexane (LCM-2, measured as $C_{17}H_{31}^+$ in the Vocus PTR-TOFMS; see *Structural Identification of LCMs and VOCs* for its identification) is 1.8 times higher in screen air than in background air (*SI Appendix*, Fig. S2). Note that the observed accumulation effect during experiments is much smaller for LCM-2 than isoprene, because LCM-2 is orders of magnitude less volatile (see the caption of *SI Appendix*, Fig. S2). The detection of LCM-2 here is consistent with a recent study, which reports its presence in indoor dust (21), further confirming LCM pollution in the indoor environment.

We also conducted experiments on a laptop screen and a TV screen and found that both screens could emit VOCs and LCMs, with results summarized in *SI Appendix*, Tables S2 and S3. Together, these results indicate that such VOC emissions may be a ubiquitous issue for all LCD screens.

Structural Identification of LCMs and VOCs. While the mass peaks in the Vocus PTR-TOFMS can help to infer the elemental formulae ($C_xH_yO_zN_j$) of detected chemicals, they cannot provide the molecular structures of these chemicals. To address this gap, we developed a workflow to elucidate the possible structures of LCD screen-emitted LCMs and VOCs (Fig. 2) using two different strategies for the identification of these two groups of chemicals.

The identification of LCMs is based upon a list of currently produced 362 LCMs, which includes the detailed information (elemental formulae and molecular structures) of these LCMs (21). With this LCM list, the LCM-related mass peaks and their corresponding elemental formulae can be “identified” with the most likely molecular structures.

In the case of VOCs, no information is currently available regarding their usage in the manufacturing of LCD screens; manufacturers often keep such information confidential. The VOC emissions from LCD screens can be explained by a “building block” hypothesis. If a chemical is used as a building block in the synthesis

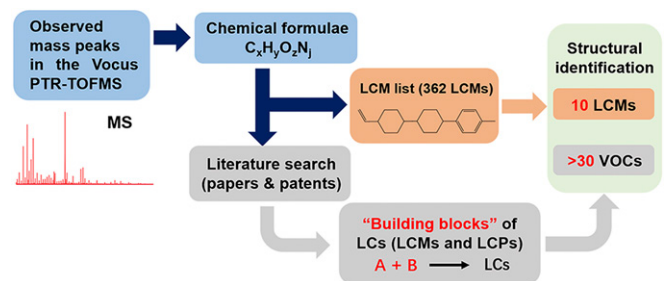


Fig. 2. Workflow for structural identification of LCD screen-emitted LCMs and VOCs. Vocus PTR-TOFMS, MS, LCs, LCMs, LCPs, and VOCs stand for Vocus proton-transfer-reaction mass spectrometry (25), mass spectrum, liquid crystals (18), liquid crystal monomers, liquid crystal polymers, and volatile organic compounds, respectively. The LCM list, which includes the detailed information of 362 currently produced LCMs, is obtained from a previous study (21). The possible links between the detected VOCs (building block chemicals) and LCs are given in *SI Appendix*, section S3 and Tables S2 and S3. The detected LCMs in this work are provided in *SI Appendix*, Table S7.

$$ER_{\text{area}} = (C_{\text{ss}} - C_0) \cdot F/A, \quad [1]$$

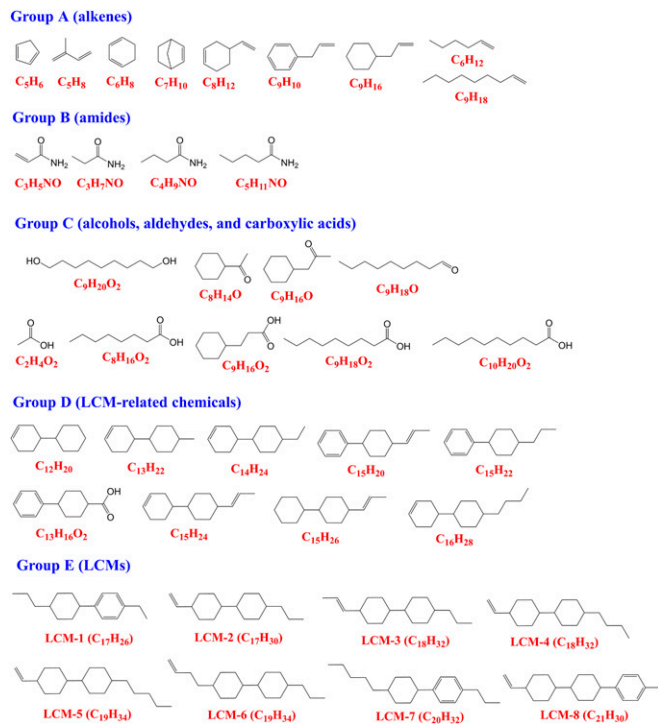


Fig. 3. Possible molecular structures of VOCs (group A to D) and LCMs (group E) emitted from a computer monitor screen.

of liquid crystals (LCs), such as LCMs and LC polymers (LCPs) (18, 27), it may reside in the LCD screens (along with LCs), thereby having the potential to be released into the surrounding air (i.e., become a VOC in air). Following this logic, the structural identification of VOCs can be achieved by combining their elemental formulae information (obtained from the Vocus measurements) with the possible links between the “building block chemicals” and LCs (obtained from previously published literature and patents; see details in *SI Appendix, section S3*).

After going through the workflow, 8 LCMs and 31 VOCs were identified from the computer monitor screen experiments, with molecular structures shown in Fig. 3. These chemicals can be divided to five groups according to their structures: alkenes (group A); amides (group B); alcohols, aldehydes, and carboxylic acids (group C); LCM-related chemicals (group D); and LCMs (group E). Of the 31 VOCs detected (group A to D chemicals), most of them (e.g., isoprene and 1,9-nonanediol) can be building blocks for LCs (28, 29), while a few (e.g., acetic acid) are the building blocks for other materials (not LCs) within LCD screens [e.g., polarizing filters, a material that allows light waves of a specific polarization to pass through (30)]. The emission of acetic acid may be partly due to O_3 reactions (the likelihood is low but cannot be ruled out), as discussed in *SI Appendix, section S3*. Group D chemicals are not LCMs but possess similar structures as LCMs (see further discussion in *SI Appendix, section S3*). Thus, they are considered to be “LCM-related chemicals.” In addition to Fig. 3, for the computer monitor, the molecular structures of all detected LCMs and VOCs from laptop and TV screens are given in *SI Appendix, Figs. S3 and S4*.

Emission Rates. Based upon the flow cell results in Fig. 1, we quantify the screen area-normalized emission rates (ER_{area} ; molecules $\cdot s^{-1} \cdot cm^{-2}$) for the detected VOCs and LCMs using Eq. 1:

where C_{ss} and C_0 (molecules $\cdot cm^{-3}$) are the steady-state and background concentrations of a VOC, respectively. F ($cm^3 \cdot s^{-1}$) is the flow rate of screen air, and A (cm^2) is the tested area of an LCD screen. It should be noted that while PTR is a fairly soft chemical ionization technique, some VOCs (e.g., aldehydes) undergo fragmentation within the PTR instrument (31). That means the smaller m/z fragments from a large molecule (e.g., fragment $C_9H_{18}OH^+$ from $C_9H_{20}O_2$; *SI Appendix, Table S4*) may cause interference in the quantification of other molecules (e.g., $C_9H_{18}O$). Hence, to obtain accurate ER_{area} , the VOC concentrations are corrected for fragmentation (*SI Appendix, sections S4 and S5*).

Fig. 4A shows the emission rates of the most abundant VOCs ($ER_{\text{area}} > 1.7 \times 10^8$ molecules $\cdot s^{-1} \cdot cm^{-2}$) emitted from computer monitor, laptop, and TV screens at 296 K and 23 to 58% RH. The estimated ER_{area} for other detected VOCs are given in *SI Appendix, Tables S2 and S3*. The three LCD screens investigated have both similarities and differences with respect to their VOC emission patterns, as discussed next. VOCs such as acetic acid,

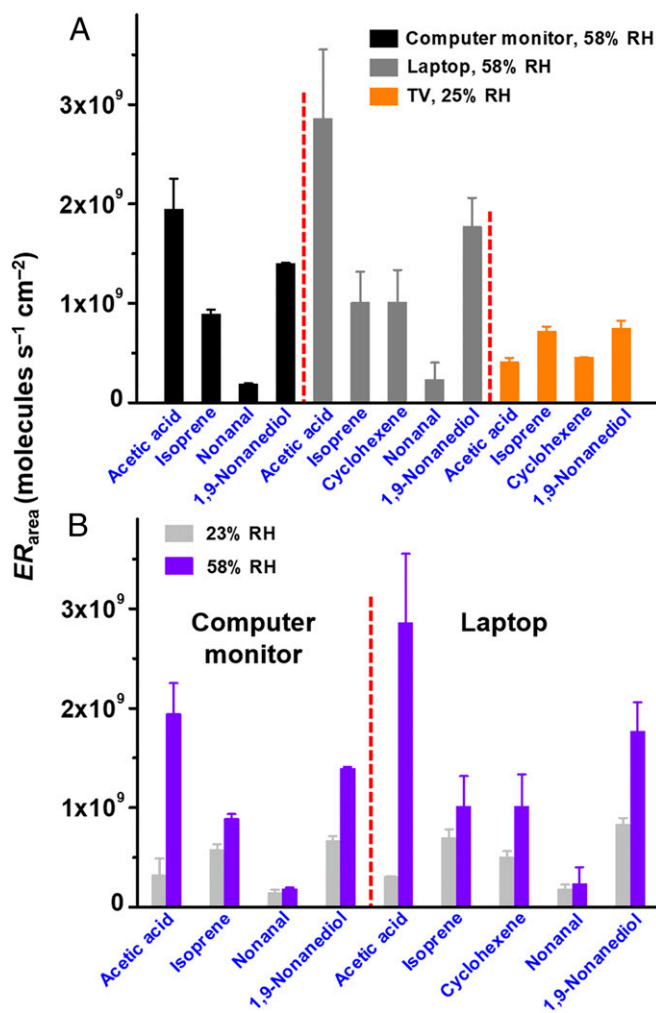


Fig. 4. (A) Screen area-normalized emission rates (ER_{area} ; molecules $\cdot s^{-1} \cdot cm^{-2}$) of the most abundant VOCs emitted from the screens of three LCDs (a new computer monitor, a used laptop, and a new TV). (B) Impact of RH on the ER_{area} of several VOCs emitted from two LCD screens (a computer monitor screen and a laptop screen). Experimental conditions are the following: genuine indoor air (in a laboratory at the University of Toronto), 296 K, and 23 to 58% RH. The ER_{area} for all detected VOCs are provided in *SI Appendix, Tables S2 and S3*. Error bars represent one SD.

isoprene, and 1,9-nonanediol were observed to be emitted from all screens with ER_{area} of up to $(2.9 \pm 0.7) \times 10^9$, $(1.0 \pm 0.3) \times 10^9$, and $(1.8 \pm 0.3) \times 10^9$ molecules \cdot s $^{-1}$ \cdot cm $^{-2}$, respectively (Fig. 4A). However, those screens also exhibit distinctly different emission patterns. For example, high levels of cyclohexene were emitted from laptop and TV screens, with ER_{area} of up to $(1.0 \pm 0.3) \times 10^9$ molecules \cdot s $^{-1}$ \cdot cm $^{-2}$, whereas that was not the case for the monitor screen. One potential explanation for the similarities and differences within the three screens is that, during the manufacturing of LCD screens, some chemicals are used in all investigated screens (corresponding to the similarities), while some are not (corresponding to the differences). Also, given that these LCD screens are produced by different manufacturers (*SI Appendix, Table S1*), the mass concentrations of various chemicals in the LC layers inside the screens may be different. This can be another possible reason for the observed differences.

For a given LCD screen, the ER_{area} of LCMs are orders of magnitude lower than those of VOCs ($< 4 \times 10^6$ molecules \cdot s $^{-1}$ \cdot cm $^{-2}$; *SI Appendix, Tables S2 and S3*). Lower emission rates for LCMs are expected because their volatilities (estimated vapor pressure < 0.58 Pa) (21) are significantly lower than VOCs (e.g., isoprene vapor pressure 7.3×10^4 Pa).

Below, we summarize other features related to LCD screen-emitted VOCs.

- 1) The ER_{TVOC} (the sum of ER_{area} of all detected VOCs; *SI Appendix, Table S5*) is 49 to 67% higher in screen air than in background air, depending upon the investigated LCD screens. This implies that LCD screens may be an important source for indoor VOCs.
- 2) As mentioned earlier, LCDs were turned off throughout the experiments. Further investigations show that the status of an LCD (on or off) has negligible impacts on its VOC emissions, suggesting that VOCs are emitted to the surrounding air with relatively constant emission rates, regardless of the status of LCDs.
- 3) The laptop screen investigated here can emit high levels of VOCs (Fig. 4A and *SI Appendix, Table S2*), although it has been used for 3 y. This indicates that the LCD screen-induced VOC emission could be a long-term issue.
- 4) In theory, LCD screens may serve as “passive samplers” for indoor air constituents (32). Under such conditions, the detected VOCs may have two sources. One is an indirect source (i.e., the air constituents that are passively collected by LCD screens during their usage). The other is a direct source (i.e., the LCs and the associated building block chemicals used in LCD screens). However, the “passive sampling” hypothesis seems unlikely given the two reasons discussed next. First, if the indirect source is the dominant source, given the ubiquitous presence of benzene and toluene (with high concentrations) in both indoor and outdoor environments (23, 24, 33, 34), we would expect to observe high emissions of these two VOCs from LCD screens, which is in contrast with the flow cell results (Fig. 3). Second, LCD screens were exposed to genuine indoor air prior to experiments, yet the concentrations of VOCs were higher in screen air than in indoor air, which cannot be explained by the passive sampling hypothesis.
- 5) During the manufacturing of LCD screens, LCMs are simply filled into the space between oriented films (a component used for aligning LCs unidirectionally) and are not chemically bonded to base materials (21). It is possible that some LCMs and VOCs are adsorbed to the outer surface of the oriented film during manufacturing. In this case, the chemicals inside the LCD screen can diffuse to the surface via two pathways. First, chemicals in the LC layer can diffuse around the oriented film and polarizing filter to reach the surface of LCD screen. Second, chemicals adsorbed on the outer surface of oriented film can diffuse around the polarizing filter to reach the surface of

LCD screen. The second pathway may play a minor role in the emission of these chemicals, as discussed in *SI Appendix, section S3*.

Impact of RH. Air humidity is a key parameter that affects indoor air quality (35, 36). A complete understanding of LCD screen-emitted VOCs also requires knowledge of the impact of RH on their emissions. The RH effect was investigated by comparing the VOC emission rates at the same temperatures (296 K) but with differing RH conditions (23 and 58% RH). As shown in Fig. 4B, the area-normalized emission rates of VOCs (e.g., acetic acid, isoprene, and 1,9-nonanediol) increased by up to a factor of 9 when the indoor RH was increased from 23 to 58%. The positive relationship between emission rates and RH also holds for LCMs, as can be seen in *SI Appendix, Fig. S5A*.

Such RH impacts are likely caused by the water–organic interactions. More specifically, water molecules diffuse into LCD screens and interact with synthetic organic chemicals inside the screens, which may lower their viscosities, thus leading to faster diffusion rates of organics (diffusion from LC layers to the surrounding air) and accelerating their emissions. The impact of RH on the viscosities of several organics with diverse structures has been demonstrated previously. For example, levoglucosan and sucrose particles underwent an RH-induced phase transition from highly viscous to a less viscous state, with an increase of RH from 20 to 60% (37, 38). Moreover, previous studies on organic particles (succinic acid and organophosphate esters) indicated that the heterogeneous OH oxidation kinetics increased by up to a factor of 41 at high-RH conditions (63 to 68%), compared to low-RH conditions (10 to 35%) due to a change in the particle viscosity with increased RH (39, 40). Therefore, a similar RH–viscosity rationale may result in the RH effect in Fig. 4B for the investigated LCD-related synthetic organic chemicals. While the most reasonable explanation for the experimental results is the RH–viscosity mechanism, other mechanisms, for example, displacement of the adsorbed organics by water molecules, are possible, as discussed in *SI Appendix, section S7*.

The observed RH effect here is consistent with previous VOC studies on other materials such as wood sills and newspaper (41, 42), which demonstrated that the emission rates of butanol (from laboratory-contaminated wood sills) and acetic acid (from newspapers) were increased by factors of 21 and 2, respectively, with an increase of RH from 20 to 40% to 50 to 85%. While the underlying mechanisms for the RH effects may be different in different types of materials (43, 44), combined together, the current and previous studies highlight the key role of RH in altering the levels of indoor VOCs.

The results in Fig. 4B were based on experiments using genuine indoor air, the RH of which was controlled by the heating, ventilation, and air conditioning (HVAC) system of the building. To investigate the RH effect over a wider RH range, we also conducted flow cell experiments with synthetic zero air (from a gas cylinder); the RH inside the flow cell was maintained at selected values in the range of 10 to 70% by controlling the flow of wet and dry zero air (*SI Appendix, Fig. S1B*). The zero air experimental results confirm the positive RH–VOC emission rate relationship observed in indoor air experiments, as shown in *SI Appendix, Fig. S5B*.

In general, there are advantages and disadvantages to using indoor air, compared to using zero air. The indoor air experiments allow us to exclude the impact of passive sampling (i.e., the advantage). The disadvantage is the potential O $_3$ reactions: O $_3$ in the indoor air may react with alkenes and contribute to the emission of aldehydes and acids (this possibility is low but cannot be completely ruled out; *SI Appendix, section S3*). These advantages and disadvantages are vice versa for the zero air experiments. Interestingly, under similar experimental conditions, the emission

rates for some VOCs are higher in indoor air experiments than in zero air experiments. Given that some alkenes (e.g., cyclohexadiene) are emitted at higher rates with indoor air than with zero air, it is unlikely that chemical reactions (e.g., ozone oxidation) are driving this effect. Rather, higher emission rates in indoor air experiments may be due to organic–organic interactions, involving organic components that are part of indoor air (see details in *SI Appendix, section S3*).

Assessing the Impact of LCD Screens on Indoor VOCs. From the perspective of indoor VOC risk evaluation, it is essential to assess the impact of LCD screens on indoor VOCs. The contribution of LCD screens to indoor VOCs is estimated using a box model (*SI Appendix, Fig. S6*). Assuming that chemical A is in steady state in a room, then the emission rate of A from internal sources within a room (ER_{internal} ; molecules \cdot s $^{-1}$) can be determined via the following equation:

$$\begin{aligned} ER_{\text{internal}} &= R_{\text{indoor}} - R_{\text{outdoor}} + R_{\text{OH}} \\ &= (A_{\text{indoor}} - A_{\text{outdoor}}) \cdot V_{\text{room}} \cdot AER \\ &\quad + k_{\text{OH}} \cdot [\text{OH}] \cdot A_{\text{indoor}} \cdot V_{\text{room}}, \end{aligned} \quad [2]$$

where R_{indoor} , R_{outdoor} , R_{OH} , V_{room} , AER , k_{OH} , and $[\text{OH}]$ are the removal rate of indoor A via ventilation (molecules \cdot s $^{-1}$), the infiltration rate of outdoor A (molecules \cdot s $^{-1}$), the degradation rate of indoor A due to OH oxidation reactions (molecules \cdot s $^{-1}$), the room volume (m 3), the air exchange rate constant (the first order rate constant at which the whole room volume air exchanges with the outdoor air; h $^{-1}$), the gaseous OH reaction rate constant for chemical A (cm 3 \cdot molecules $^{-1}$ \cdot s $^{-1}$), and indoor OH concentration (1.2 \times 10 5 molecules \cdot cm $^{-3}$) (45), respectively. In this model, we assume chemical A possesses a steady-state concentration in both indoor (A_{indoor} ; molecules \cdot cm $^{-3}$) and outdoor air (A_{outdoor} ; molecules \cdot cm $^{-3}$). As numerous commercial chemicals are used indoors, the concentrations of many VOCs are higher indoors than outdoors (46, 47) (i.e., $A_{\text{indoor}} > A_{\text{outdoor}}$).

With the calculated ER_{internal} , the LCD screen contribution to indoor A (LCD $_{\text{contribution}}$; %) can be estimated using Eq. 3:

$$\text{LCD}_{\text{contribution}} = \frac{ER_{\text{area}} \cdot A_{\text{LCD}} \cdot Q_{\text{LCD}}}{ER_{\text{internal}}} \cdot 100\%, \quad [3]$$

where ER_{area} is the screen area–normalized emission rate of chemical A (obtained from Eq. 1), A_{LCD} is the effective area of an LCD screen (cm 2 \cdot unit $^{-1}$), and Q_{LCD} is the quantity of LCD screens in a room (unit). Note that for isoprene, the impact of O $_3$ oxidation reaction is also considered in the calculations (48), with details given in *Materials and Methods*.

We assume six computer monitors ($Q_{\text{LCD}} = 6$ units) are used in an office of 40 m 3 ($V_{\text{room}} = 40$ m 3) at 58% RH, simulating a real-life scenario. Air exchange rates are not uniform across different buildings, depending upon their HVAC systems. For that reason, two scenarios, including a low– (scenario 1; $AER = 0.5$ h $^{-1}$) and high– (scenario 2; $AER = 5$ h $^{-1}$) air exchange rate scenario (49–51), are explored, representing an upper and a lower limit for LCD $_{\text{contribution}}$. Other parameters implemented in the model are given in *SI Appendix, Table S6*. As illustrated in Fig. 5, in scenario 1, the LCD $_{\text{contribution}}$ for acetic acid, isoprene, and nonanal (three well-studied indoor VOCs) (52–54) are 5, 6, and 4%, respectively, while 1,9-nonanediol, a less-studied indoor VOC with limited knowledge on its source, possesses a higher LCD $_{\text{contribution}}$ (18%). The LCD $_{\text{contribution}}$ for these four VOCs decrease to 0.4 to 1.8%, with an increased AER in scenario 2. While the calculated LCD $_{\text{contribution}}$ are clearly affected by the input parameters (Q_{LCD} , V_{room} , AER , and RH), the estimates in Fig. 5 demonstrate that LCD screens can make substantial

contributions to indoor VOCs under certain conditions. Additionally, we recognize that the relative contributions may be smaller under specific scenarios [e.g., human breath contains high isoprene mixing ratios (55)]. We also note that the ER_{TVOC} of LCD screens (1.5 to 4.9 $\mu\text{g} \cdot \text{h}^{-1} \cdot \text{unit}^{-1}$; *SI Appendix, Table S5*) are substantially lower than the ER_{TVOC} of, for example, hardboard, plywood, and new furniture (> 10 mg \cdot h $^{-1} \cdot \text{unit}^{-1}$) (56, 57). Despite this, the short distance between humans and LCDs (e.g., laptops) during their usage increases the probability for humans to inhale the LCD screen-emitted chemicals.

This work demonstrates that LCD screens are a previously unrecognized source for indoor VOCs. It also highlights the LCM pollution in indoor environments, which could be an emerging environmental and health issue, as suggested by recent studies (21, 58). Although some of the VOCs detected are unlikely to be toxic (e.g., isoprene or acetic acid), the adverse health effects associated with VOCs in general (6–8) and the recently demonstrated toxicity of LCMs (21) emphasizes the need to further investigate the identification, environmental fate, and toxicological effects of the chemicals emitted from LCD screens.

Materials and Methods

Flow Cell System. The experimental system includes two rectangular flow cells, in which one was placed on an LCD screen (screen flow cell) and the other one was placed on a glass plate (glass flow cell). The use of screen and glass flow cells allows the measurements of VOCs in screen air and background air, respectively. The surfaces of the LCD screen and glass plate were cleaned with ultrapure water before experiments. Further details regarding the flow cells, experimental setup, and experimental procedure are provided in *SI Appendix, section S1 and Fig. S1*.

Vocus PTR-TOFMS Measurements. The VOCs and LCMs emitted from LCD screens were measured with a Vocus PTR-TOFMS (Aerodyne Research; *SI Appendix, section S2*) (25). Sample air was drawn in through a 2m-long PFA Teflon tubing (inside diameter 3.97 mm, outside diameter 6.35 mm), with a flow rate of 350 cm 3 \cdot min $^{-1}$. Only 100 cm 3 \cdot min $^{-1}$ of this flow was sampled into the Vocus, and the remainder (250 cm 3 \cdot min $^{-1}$) was directed to a KNF diaphragm pump (model UN911 KVP). The Vocus was operated according to the following parameters: focusing ion–molecule reactor pressure 2.2 mbar, water flow 20 cm 3 \cdot min $^{-1}$, discharge voltage 425 V, discharge voltage current 2 mA, and $E/N = 79$

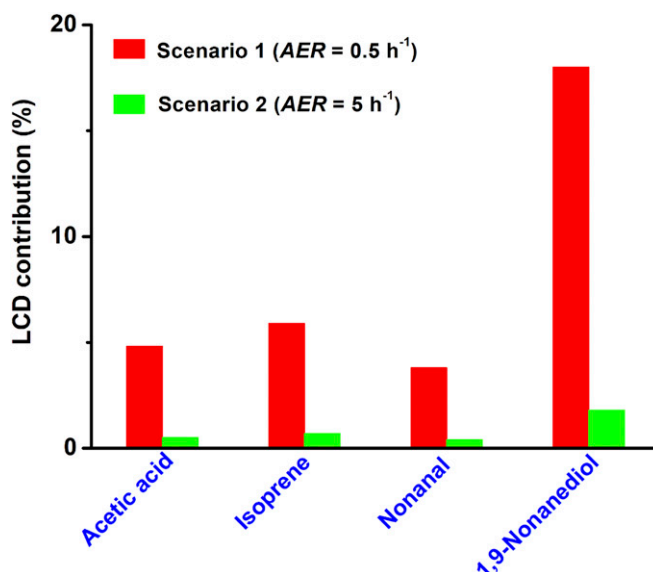


Fig. 5. Estimated contributions of LCD screens (%) to indoor VOCs. This estimation is based on a real-life scenario: six computer monitors are used in an office of 40 m 3 at 58% RH, with an air exchange rate (AER) of 0.5 to 5 h $^{-1}$ (49–51). All parameters used in the calculations are given in *SI Appendix, Table S6*.

Td. The mass resolution at m/z 200 was 8,000. Data were recorded with a time resolution of 1.5 s and analyzed using Tofware software (version 3.2.0).

The Vocus was calibrated with isoprene (460 ppb from a gas cylinder) after each flow cell experiment, providing a day-to-day record of instrumental sensitivity. We also performed calibration experiments for a few other VOCs using a "syringe pump" approach (SI Appendix, section S4). Previous studies have suggested that the sensitivities of VOCs are linearly related to their proton transfer reaction rate constants ($k_{\text{proton-transfer}}$; $\text{cm}^3 \cdot \text{molecule}^{-1} \cdot \text{s}^{-1}$) (25, 59, 60). Thus, an empirical relationship between the sensitivity and $k_{\text{proton-transfer}}$ can be obtained from the calibration results: sensitivity ($\text{cps} \cdot \text{ppb}^{-1}$) = $6.41 \times 10^{11} k_{\text{proton-transfer}}$ (SI Appendix, Fig. S7D). Once $k_{\text{proton-transfer}}$ is available (SI Appendix, section S5), the sensitivity of a VOC can be predicted.

Estimation of LCD_{contribution} for Indoor Isoprene. An accurate estimation of the contribution of LCD screens to indoor isoprene should consider its O_3 and OH oxidation reactions. In this case, the LCD_{contribution} can be determined via Eq. 4:

$$\text{LCD}_{\text{contribution}} = \frac{ER_{\text{area}} \cdot A_{\text{LCD}} \cdot Q_{\text{LCD}}}{(A_{\text{indoor}} - A_{\text{outdoor}}) \cdot V_{\text{room}} \cdot AER + (k_{\text{OH}} \cdot [\text{OH}] + k_{\text{O}_3} \cdot [\text{O}_3]) A_{\text{indoor}} \cdot V_{\text{room}}} \cdot 100\%, \quad [4]$$

where k_{OH} and k_{O_3} are the gaseous isoprene–OH ($1 \times 10^{-10} \text{ cm}^3 \cdot \text{molecule}^{-1} \cdot \text{s}^{-1}$) and isoprene– O_3 ($1.27 \times 10^{-17} \text{ cm}^3 \cdot \text{molecule}^{-1} \cdot \text{s}^{-1}$) reaction rate constants, respectively (61). [OH] and [O₃] are the indoor OH ($1.2 \times 10^5 \text{ molecules} \cdot \text{cm}^{-3}$) and O₃ concentrations ($2.95 \times 10^{11} \text{ molecules} \cdot \text{cm}^{-3}$; SI Appendix, Table S6), respectively (45). In general, the gaseous O₃ and OH reactions have little impact on the concentrations of indoor unsaturated VOCs and LCMs, as shown in SI Appendix, section S7.

Data Availability. All study data are included in the article and/or SI Appendix.

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