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Liquid Crystal Monomers: Global Indoor Air Contaminants of Emerging Concern

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A B S T R A C T

Liquid crystal monomers (LCMs), critical components of liquid crystal displays (LCDs) found in everyday electronic devices, have recently been identified as emerging indoor air contaminants. Due to their persistence, bioaccumulation, and toxicity, LCMs pose a potential risk to human health, especially as people spend significant time indoors. This review synthesizes findings from global studies on the occurrence, concentration levels, exposure routes, and potential health impacts of LCMs. Results reveal widespread presence of LCMs indoors, with dust ingestion and dermal absorption identified as major exposure pathways, particularly affecting infants and children. Experimental studies suggest that LCMs may cause cytotoxicity, oxidative stress, endocrine disruption, and other adverse effects, although conclusive human health impacts remain under-researched. The review highlights critical knowledge gaps, stressing the need for further epidemiological studies, standardized methodologies, and enhanced indoor air quality monitoring to better understand and mitigate the risks associated with LCM exposure.

Keywords: Liquid crystal monomers; contaminants of emerging concern; indoor air contaminants; environmental health; liquid crystal displays

1. Introduction

Contaminants of emerging concern (CECs) or pollutants of emerging concern are a significant and large class of environmental contaminants/pollutants from human-induced activities.(Cetinkaya et al., 2025; Y. Y. Zhang et al., 2025) Liquid crystal monomers (LCMs) have been proposed as a novel class of emerging pollutants.(S. Zhang et al., 2022) LCMs are a family of synthetic organic chemicals which are intermediate between liquid and solid states at normal ambient temperatures, and this characteristic makes them a critical component of liquid crystal displays (LCDs) of various electric and electronic products (e-products).(Cheng et al., 2023; Su et al., 2019) LCDs are found in daily use items ranging from small hand-held calculators, smart watches, mobile phones, digital cameras, tablets, game consoles, laptops and desktop computers to large-sized displays such as flat-screen televisions, large-screen monitors, solar panels, and other intelligent electronic products for communication, study, work, and entertainment.(Cenci et al., 2022; Chandel et al., 2022; Jin, Fan, et al., 2023; Q. Liu & Abbatt, 2021; Yao et al., 2023) LCD screens can release their LCM contents into the indoor environment (whether the devices are running or not),(Jin, Yu, et al., 2023; Q. Yang et al., 2025) and this is concerning as LCMs have been identified as an emerging group of potentially persistent, bio-accumulative, toxic, and long-range atmospheric transport pollutants.(Lin et al., 2024; Su et al., 2019; Q. Yang et al., 2025) In addition, humans spend about 90% of their time living or working indoors,(Q. Liu & Abbatt, 2021) and LCMs persist 10-150 times longer indoors compared to outdoors,(Miramontes Gonzalez & Li, 2024) making the indoor environment an intense exposure site for humans.

Although LCDs were discovered more than a century ago (in the 1880s),(R. Li et al., 2023; Thanh & Ayan Au, 2023) they were commercially produced in large scales around four decades ago (in the 1980s),(Thanh & Ayan Au, 2023) but were only challenged for the potential toxicities of their LCMs-content in 2018.(J. Li et al., 2018) LCD panels are mainly produced in 3 Asian countries: China, Japan, and South Korea; with China being the world's largest producer of the latest generation LCD panels.(Su et al., 2019) With the increasing modernization of human lifestyle globally, the production of LCD panels increased by 4900% between 2000 and 2018 (from 2 million m2 to 198 million m2).(R. Li et al., 2023; L. Y. Liu et al., 2023) Current LCD-containing devices are usually composed of more than 10-20 LCMs,(H. Li et al., 2024; Su et al., 2024) and mobile phones were the most popular LCD device with up to 70.3% (i.e. 5.75 billion) of the world's total population using mobile phones as of October 2024.(Kemp, 2024) Despite this, people do not know the environmental effects of LCMs.(Su et al., 2019)

In the light of over 10,000 LCMs analogues currently synthesized for commercial purposes,(C. Li et al., 2021) and an estimated 1.07–107 kg of LCMs directly released into the environment per annum worldwide,(Liang et al., 2021) most LCM manufacturers have announced that the LCMs do not pose significant risks to organisms and the environment.(Stadelmann et al., 2024) However, the increasing focus on environmental pollution has led to the further identification and characterization of LCMs and transitioned them from the initially celebrated unique chemicals to contaminants of significant concern.(F. Wang et al., 2024) Despite the ubiquitous and emerging toxic nature of LCMs, their overall characteristics have not been fully studied.(Q.

Liu & Abbatt, 2021; Su et al., 2019) Thus, this synthesis of knowledge on the occurrence, concentration levels, main intake/exposure routes, most exposed groups, and potential health impacts of LCMs is very timely in the current need to study a globally distributed emerging indoor air pollutant.

1.1 Objectives

The primary objectives of this review were to: (i) Review the occurrence and concentration levels of LCMs in indoor environments globally; (ii) Establish the main intake/exposure routes and most exposed groups to LCMs in indoor environments globally; (iii) Review the level of potential or established health impacts from exposure to LCMs in indoor environments globally; and (iv) Raise concerns and directions/areas for future research.

2. Materials and Methods

This review synthesizes findings from recent studies published between 2018 and January 2025 on PubMed, Scopus, Web of Science, and Google Scholar databases using keywords including “liquid crystal monomers”, “contaminants of emerging concern”, “indoor air pollution”, “electronic devices”, “liquid crystal displays”, “human exposure”, and “environmental health”. Studies were selected based on relevance, recency, and the robustness of their methodologies.

3. Results and Discussions

3.1 Occurrence and concentration levels of LCMs in indoor environments globally

The available studies on LCMs in indoor air were mainly from Asia, Europe and North America, and the occurrence and concentration comparisons were only available for three countries (China, Sweden, and the USA). The indoor environments studied were mainly residential (homes and dormitories) and non-residential (offices, pre-school, park, laboratory etc.) sites. As shown in Table 1, the sample sizes ranged between 12 and 112 indoor sites per study.

There are difficulties in the dentification of LCDs in the environment due to manufacturers’ confidentiality on the formulas used in their production.(Cheng et al., 2023) Nevertheless, between 2018 and 2024, 12-64 target LCMs were studied, and 3-47 of the LCMs were detected in indoor environments in each of the studies. These studies showed that among the residential homes, the lowest mean ΣLCM concentration was 87.2ng/g in China,(S. Zhang et al., 2022) and the highest mean ΣLCM was 2,030ng/g in the USA.(Y. Liu et al., 2024) Among the residential homes, the median ΣLCM concentrations from indoor dust ranged from 12.00ng/g in Beijing China,(R. Yang et al., 2023) to 402 ng/g in 16 States of the USA.(Y. Liu & Kannan, 2024) The highest median ΣLCM concentration of 67,400ng/g was recorded within the indoor environment of an electronic waste recycling industrial park in Central China.(Cheng et al., 2022) These results indicate the extensive occurrences of LCMs in indoor environments.

3.2 Occurrence and concentration levels of LCMs in indoor environments globally

LCMs are not covalently bonded to any host materials in LCDs thus they are emitted into the environment during the production, use, disposal, and recycling of electronic products.(Q. Yang et al., 2025) LCMs have been detected on human skin, in indoor dust, air, food, human serum and breastmilk.(R. Li et al., 2023; Stadelmann et al., 2024; Su et al., 2024; Thanh & Ayan Au, 2023; Wu et al., 2025; R. Yang et al., 2023) The major intake pathways of LCMs emitted into the environment were dust ingestion and dermal absorption including direct contact with LCD screens (Table 1). The major intake pathway for infants is through breast milk, which also reflects the mother’s exposure.(R. Yang et al., 2023) Other main pathways of intake of LCMs are inhalation and dietary exposure.(Jin, Fan, et al., 2023; Y. Wang et al., 2024)

Across several studies, younger persons (infants, toddlers, children) were the most exposed to LCMs, compared to adults.(Huang et al., 2022; H. Li et al., 2024; Y. Liu & Kannan, 2024; R. Yang et al., 2023; Yao et al., 2023) Younger children may face higher exposure doses due to their behaviours, such as hand-to-mouth activities and proximity to dust-laden surfaces. In addition, there was a positive relationship of indoor ventilation on habits (hours per day) and a significant negative correlation of the frequency of cleaning per month, and the level of LCMs in the dust.(R. Yang et al., 2023) The implication is that ventilation and frequent cleaning of the indoor environments could aid the control of exposure to LCMs by the removal of dust from the indoor environment.

Table 1 - LCM Studies in indoor settings across the globe.

Country	**Site**	**Setting**	**Sample size**	**Number of LCMs measured**	**Number of LCMs detected**	**Unit**	**Mean ∑LCM**	**Median ∑LCM**	**Range ∑LCM**	**Main intake route**	**Most exposed group**	**Health impacts**	**Study**
ASIA:													
China	Beijing	Residences	112	37	32	ng/g	-	54.7	17.8-197	• Dust ingestion • Dermal contact	Younger people	Insignificant	Li *et al*. (2024)
China	Beijing	Residences	93	39	37 (dust) 30 (breast milk)	ng/g ng/g lw	-	12.00 133.40	4.33-121.15 11.97-28200	• Homogenized dust • Breast milk	Infants	Low health risk	Yang *et al*. (2023)
China	Hong Kong	Residence, Lab, Lecture theatre, Metro subway	49	64	31	ng/g	169	-	43.7-448	Indoor ventilation & air conditioning filter dust	-	Oxidative stress in human lung cells	Jin *et al*. (2023)
China	Nanjing	Residences	53	33	17	ng/g	-	-	0.13-2213	Indoor dust	-	-	Su *et al*. (2019)
China	Central China	Recycling Industrial Workshop	53	55	45	ng/g	-	67,400		• Dust ingestion • Dermal contact	-	-	Cheng *et al*. (2022)
China	Yulin	Dorm, Teaching, and Laboratory buildings	20	35	35	ng/g		153	48.6-396	Dust ingestion	Dormitory residents	Little health risk	Su *et al*. (2024)

China	Guiyu & Jiedong	Residences		57	46	pg/m^3	-	-	0.970–1080 2.853–455	Inhalation	Toddlers	-	Yao *et al*. (2023)
China	Nation-wide	Dwellings	48	60	8	ng/g	87.2	41.6	17.3-529	• Dust ingestion • Dermal contact	Children	-	Zhang *et al*. (2022)
EUROPE:													
Sweden	Örebro	Households, Offices, Pre-schools, Stores	30	12	3	ng/g	-	195	Not detected to 1586	-	-	-	Dubocq *et al*. (2021)
Sweden	Örebro	Homes, Stores, Lab, Recycling center	10	13	5	ng/g	-	-	63-430	Indoor walls & underneath furniture	-	-	Haggblom *et al*. (2022)
NORTH AMERICA:													
United States	16 States	Residences	104	60	47	ng/g	-	402	Not detected to 4300	• Dust ingestion • Dermal contact	Children	-	Liu *et al*. (2024)
United States		Residential homes	10	60	42	ng/g	2030	-	622-5400	• Indoor dust	-	-	Liu *et al*. (2024)

The level of potential or established health impacts from exposure to LCMs in indoor environments

More than half of LCMs contain environmentally hazardous groups (fluorophenyl, cyanophenyl, and diphenylacetylene), and are mainly classified as bio-accumulative, persistent and toxic (PBT) with long-range transport potential.(Jin, Fan, et al., 2023; Kong et al., 2023; C. Li et al., 2021; Yao et al., 2023) Some experimental studies consequently predicted acute and chronic toxicity of LCMs to fish, green algae, daphnia, chicken embryos.(Ge et al., 2023; Huang et al., 2022; C. Li et al., 2021) These in vitro studies have indicated that exposure to LCMs can lead to adverse effects like cytotoxicity, oxidative stress, metabolic disorders, endocrine disruptions, and alterations in gene expression.(Y. Wang et al., 2024) However, current data on the established health risks of exposure to LCMs in vivo are limited, and further research is needed to elucidate their toxicological profiles.

4. Conclusion

Liquid crystal monomers are an emerging group of environmental pollutants frequently found indoors where a lot of LCM-containing LCD-devices are used. Studies have shown their occurrence in high concentrations in indoor environments across countries, and they are recently classified as potentially persistent, bio-accumulative, and toxic. Studies on fishes and in-vitro human cells have predicted some adverse health effects. And analyses of LCM concentrations in human biological samples such as serum and breast milk suggest potential bioaccumulation, particularly in infants and toddlers. However, there are no studies conclusively linking these emerging pollutants to specific human diseases yet.

4.1 Limitations/Constraints

This study presents a comprehensive review of LCM occurrence, exposure pathways, and potential health effects. However, several limitations are acknowledged:

Limited geographic coverage: Most of the reviewed studies originate from Asia, Europe, and North America. This limits the generalizability of findings to regions where data is scarce.

Variability in methodologies: Different studies employed diverse sampling techniques, analytical methods, and reporting formats, making direct comparisons challenging. Standardized methodologies are needed for more accurate global assessments.

Confidentiality in manufacturing processes: The proprietary nature of LCD formulations restricts access to detailed chemical compositions of LCMs, which delay identification and risk assessment.

A paucity of longitudinal health studies: While in vitro and ecological studies suggest potential toxic effects, there is a dearth of longitudinal human studies linking LCM exposure to specific health outcomes. More epidemiological research is necessary to establish causation.

4.2 Recommendations

This study recommends the following directions and areas for future research:

- There is a need for further studies and research on the health risks associated with LCMs in humans, in light of their potentially persistent, bio-accumulative, and toxic characteristics.
- Further studies on the environmental behavior of LCMs and an elucidation of all routes of exposure are required, these will aid in understanding and mitigating exposure to LCMs since human exposure seems inevitable at the moment.
- Following the significantly higher levels of LCMs in indoor (and outdoor) air around disposal/recycling sites, there is a need to promote safe disposal and recycling of electronic devices to minimize the release of LCMs.
- Indoor Air Quality Monitoring: Regular monitoring of indoor environments, especially in areas with high use of electronic devices, for LCM concentrations is recommended, with promotion of practices to reduce exposure, such as regular cleaning to minimize dust accumulation.
- Collectively, the reviewed studies underscore the urgent need for continuous monitoring of LCM exposure in different demographic groups and future research should prioritize the development of risk assessment frameworks to assess the environmental and health impacts of LCMs.

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