SWEDISH ENVIRONMENTAL PROTECTION AGENCY

NATIONAL ENVIRONMENTAL MONITORING COMMISSIONED BY THE SWEDISH EPA

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Literature survey on the environmental contamination of liquid crystal monomers (LCMs) and a pilot study on their occurrence in sewage sludge from Sweden

Report authors

Thanh Wang[1,2], Ayan Au Musse[1]

[1]Örebro University

[2]Linköping University

Responsible publisher

Linköping University

Postal address

Department of Physics, Chemistry and Biology (IFM), Linköping University, Linköping, SWEDEN

Telephone

+46 13 284099

Report title and subtitle

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Purchaser

Swedish Environmental Protection Agency,
Environmental Monitoring Unit
SE-106 48 Stockholm, Sweden

Keywords for subject

Liquid crystals, liquid crystal monomers, sewage sludge, organic contaminants, new emerging risk chemicals

Period in which underlying data were collected

2021-2023

Sammanfattning

LCD-skärmar (Eng. Liquid Crystal Displays) dominerar för närvarande bildskärmsmarknaden och används i allt från små miniräknare till stora plattskärms-TV. Flytande kristallmonomerer (Eng. liquid crystal monomers, LCMs) är viktiga komponenter i LCD-skärmar och har producerats i stor skala sedan 1980-talet. På senare tid har det uppstått oro kring potentiella miljöutsläpp av LCMs, då nya studier har upptäckt deras förekomst i inomhusdamm, sediment, jord och till och med i människor. Det stora antalet LCMs och deras strukturella mångfald innebär utmaningar för kemisk analys. Vidare finns det skillnader i förkortningar mellan olika studier, vilket understryker behovet av en standardiserad nomenklatur för rapportering av LCMs.

Studier kring fysikalisk-kemiska egenskaper, atmosfärslivslängd och bioackumuleringspotential belyser de potentiella egenskaper hos många LCMs som är utmärkande för långlivade organiska föroreningar. LCMs kan släppas ut i miljön under tillverkning, produktanvändning och återvinningsprocesser. Miljöövervakning av LCMs är ännu i ett tidigt skede, med begränsad information kring miljöhalter. Studier har rapporterat förekomst av LCMs i inomhusdamm, utomhusmiljöer, jord, sediment och biota, men främst från Kina. Människlig exponering har föreslagits vid arbetsmiljöer och det har påvisats korrelationer mellan LCMs-nivåer i inomhusdamm och bröstmjölk från mödrar. Det behövs dock fler studier från andra länder för att bedöma om LCMs har utbredd global kontaminering.

Inom denna aktuella rapport har en pilotstudie genomförts med syfte att undersöka förekomsten av utvalda LCM i avloppsslam. Utmaningar under analysmetodens utveckling med provextraktion och provbehandling ledde dock till lågt utbyte av spikade nativa LCMs, vilket indikerar behovet av ytterligare metodoptimering. En tydlig slutsats kan därför inte dras om LCMs förekommer eller inte i svenskt avloppsslam.

Summary

Liquid crystal displays (LCDs) are currently the predominant display technology in the market and utilized in various devices from small calculators to large flat-screen TVs. Liquid crystal monomers (LCMs) are essential components of LCDs and have been produced at a large scale since the 1980s. Concerns have arisen about the potential environmental release of LCMs, with recent studies detecting their presence in indoor dust, sediments, soils and even in humans. The large number of LCMs and their structural diversity poses challenges in chemical analysis. Furthermore, there are discrepancies in acronyms between different studies, which emphasize the need for a standardized nomenclature for reporting LCMs.

Experimental data on physical-chemical properties, atmospheric lifetimes, and bioaccumulation potential highlight the potential persistent organic pollutant characteristics of many LCMs. LCMs can be released to the environment during manufacturing, product use, and recycling processes. Environmental monitoring of LCMs is in its early stages, with limited data available. Studies have reported LCM presence in indoor dust, outdoor environments, soil, sediment and biota, primarily from China. Human exposure has been suggested through occupational settings and there have been positive correlations between LCM levels in indoor dust and human breast milk. However, more studies are needed from other countries to assess whether LCMs have widespread global contamination.

Within this current report, a pilot study was conducted with the aim to investigate occurrence of selected LCMs in sewage sludge. However, challenges during analytical method development with the sample extraction and pretreatment steps led to low recoveries of native LCMs, indicating the need for further method optimization. A clear conclusion can therefore not be made whether LCMs are present or not in Swedish sludge.

Table of Contents

1. Frame of the study

Liquid crystal displays (LCDs) are currently the leading display technology in the commercial market. They are used in a wide variety of display devices ranging from small hand-held calculators, mobile phones, laptops and desktop computers to large-sized displays such as flat screen TVs. A key component of LCDs is the liquid crystal monomers (LCMs) that have been commercially produced at large scale since the 1980s. Due to their widespread usage, there is a possibility that LCMs can be released from products and emitted to the environment. Some LCMs can also exhibit persistent and hazardous properties and researchers have recently detected LCMs in various environmental matrices such as indoor dust, sediments and soils. This report aims to survey the available information about the usage, physical-chemical properties and environmental contamination of LCMs.

2. Background

2.1. Liquid crystals

Liquid crystals (LCs) are a state of matters that are intermediate between crystalline solid and normal liquid in terms of structure and molecular organization. They were earliest reported by the Austrian botanist Friedrich Reinitzer in 1888 who observed the unusual melting properties of cholesteryl benzoate (Castellano, 2005). When he heated the compound, the crystal melted at 145°C but was opaque instead of a normal clear isotropic liquid. Upon further heating, the opacity disappeared at 178°C, and later also found these could rotate polarized light. This new state of matter was further systematically investigated by the German physicist Otto Lehman who later coined the term liquid crystals. In the early 1900s, Charles Mauguin reported the optical characteristics of the twisted nematic structure of liquid crystals, and intense research on the different physical and electrical properties of LCs was conducted in the following decades. In the early 1970s, George Gray and his team at the University of Hull synthesized 4-cyano-4'pentylbiphenyl (abbreviated 5CB), which was a stable liquid crystal and could undergo phase transitions at room temperature (Lorch, 2022). Importantly, their orientation could be changed by electric fields thus changing the optical properties of the liquid crystal cells. This was one of the starting points for the wide-spread commercialization of LCs in the use of liquid crystal displays (LCDs).

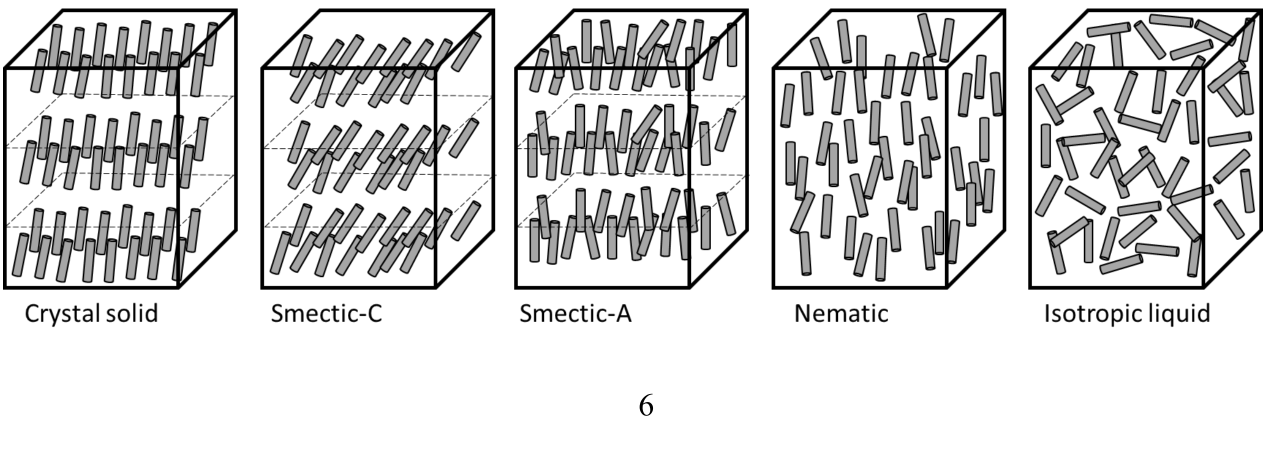


Figure 1. Schematic depiction of different phases of rod-like molecules. Modified from Yang and Wu (2015) with permission.

Liquid crystals can be roughly divided into liquid crystal monomers (LCMs) and liquid crystal polymers (LCPs). Liquid crystal monomers are typically rod-like (calamitic) or disk-like (discotic) organic molecules (Yang and Wu, 2015). The temperature is usually the determining factor for the transition between phases of LCMs. As depicted in Figure 1, the calamitic LCMs can be represented as rods. These rod-like molecules are in an isotropic liquid state at high temperature without any positional or oriental order. Upon the decrease of temperature, the LCMs are in the nematic phase where they have orientational order but no positional order. The long axis of the rods has a preferred direction, but they can still diffuse around. With a further decrease of temperature, the material transitions to higher positional and orientational order as seen from the smectic phases to the crystal solid phase. The polarizing abilities of LCMs can therefore be changed upon the transitioning between phases and molecular polarizabilities along their long and short axes (Yang and Wu, 2015). Therefore, the polarizing potential of LCMs can be adjusted by applying or removing an electric field (as well as its strength).

2.2. Applications

The development of twisted nematic LCs alongside with improvement in manufacturing technologies led to the boom of LCD industry in the 1980s (Kim and Song, 2009). Although initially used in small displays such as hand-held calculators, the further development of new technologies allowed LCDs to be used at larger displays. During the 2000s, the production of LCD televisions surpassed those of the cathode-ray tube-based TVs. Currently, almost all LCDs in the commercial market use the nematic type of liquid crystals (Jones, 2018).

The unique polarizing abilities of liquid crystals and their general use in LCD can be exemplified in Figure 2. In the LCD, a light source is provided at the back of the panel which passes the first polarizing filter. When no electric field is applied, twisted phase of the LCM reorients the polarized light from the first filter which allows the light to pass the second polarizing filter which is oriented 90° to the first filter. The spot on the display (a pixel) therefore appears transparent or bright. When an electric field is applied through the electrode, the LCMs reorient in perpendicular direction and the light rays are not twisted, thus cannot pass the second filter. This pixel is therefore opaque. The LCD image can be controlled by switching the electric field on and off as well as controlling the applied voltage.

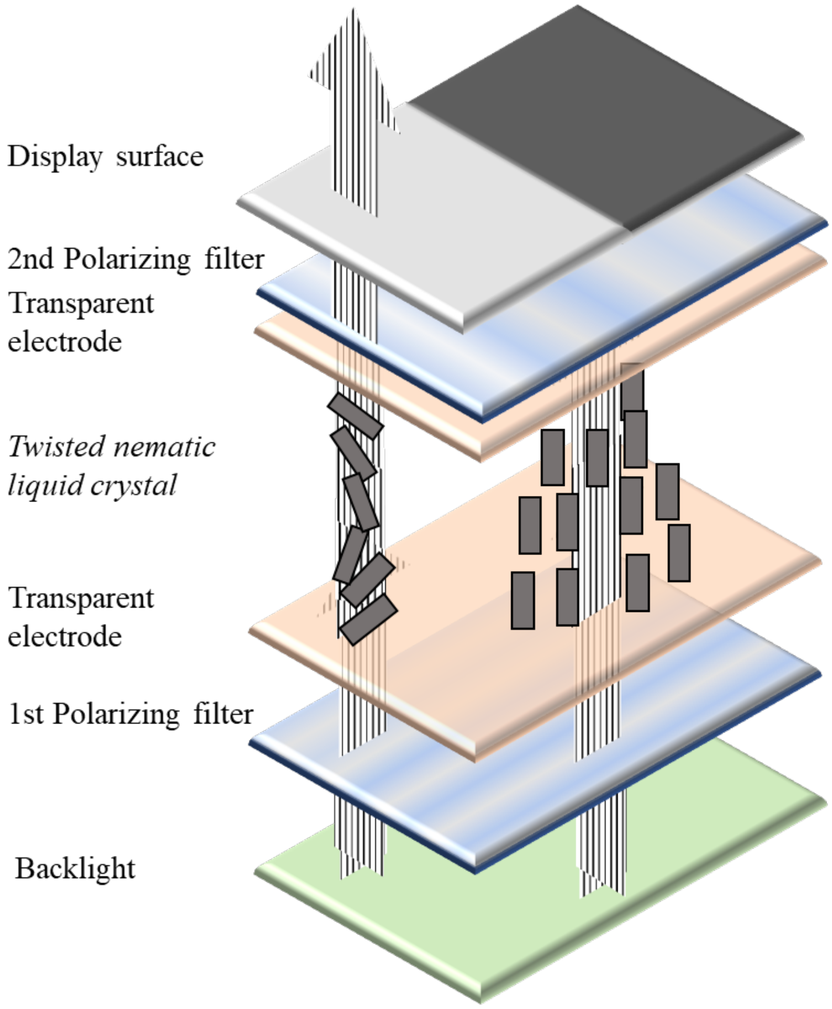


Figure 2. Simplified view of twisted nematic liquid crystal display. An example of two light rays from the backlight that are polarized to the same direction by the first filter. When no electric field has been applied the light ray on the left has been twisted by the helically arranged liquid crystal molecules and can pass the second orthogonal polarizing filter. The display surface at this pixel therefore becomes bright. When an electric field has been applied as shown to the right, the molecules align perpendicular to the electrode and lose their twisting ability. The light at this pixel has been blocked by the second filter and appears opaque.

2.3. Structures of LCMs

Liquid crystals typically consist of a rigid core and flexible tails to display the desirable properties used in LCDs. The material will have difficulty to maintain oriental order if the molecule is too flexible, while too rigid a molecule will lead to the material transitioning directly from isotropic liquid phase to crystalline solid phase without the intermediate liquid crystal phase (Wu et al., 2014). Therefore, most LCMs have aromatic cores with terminal groups that can easily be modified to change their optical and physical properties (Sargazi et al., 2019).

The typical structure of nematic LCMs, the most widely used liquid crystals in LCD panels, can be seen in Figure 3. They usually consist of ring structured subunits (A, A’) that can be connected by a linkage group (Z) forming the core. Various terminal groups (R, R’) are then attached to the core at both ends. The terminal groups usually consists of polar terminal groups (e.g. CN or NO) at one end and a nonpolar hydrocarbon chain (e.g. alkyl groups) at the other end, while the core is usually aromatic which provides chemical stability (Jain and Deshmukh, 2020).

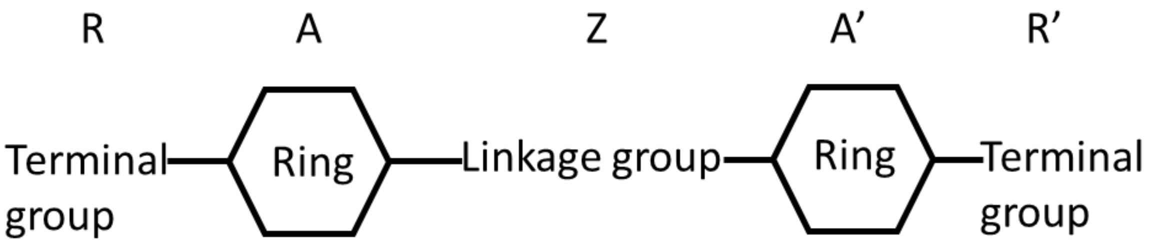
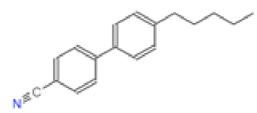
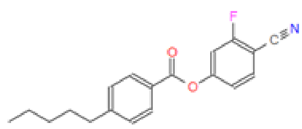
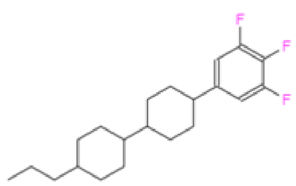
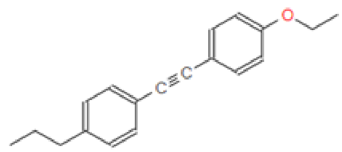
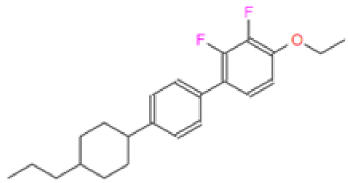
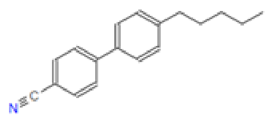
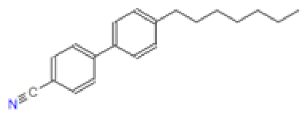
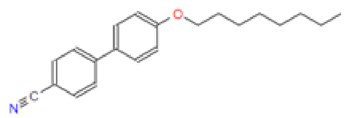
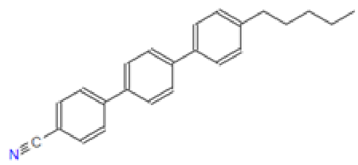


Figure 3. General structure of nematic LCMs.

Over the years, new LC materials have been developed to increase the efficiency and applicability of LCDs such as polarization ability, response time and operation temperature range. The properties of liquid crystals can be adjusted by using different cores as well as terminal groups. The incorporation of fluorinated substituents can also greatly change the physical properties of liquid crystals due to their small size and high polarity (Hird et al., 2003, Hird and Toyne, 1998). LCMs are usually used in different mixtures in LCDs. A mixture of 10-20 different LCMs is common used in one LCD panel (Klasen-Memmer and Hirschmann, 2012). Table 1 shows the information of several typical LCMs together with their structures. As can be seen, these compounds share common features such as linearly linked aromatic or cyclic hexane cores and various terminal groups with different chain lengths and functional groups. A common commercial mixture (E7) is also provided in Table 1 together with the percentage composition of the individual LCMs.

Table 1. Some common nematic liquid crystal monomers and their chemical structures.

IUPAC name	Chemical formula	CAS	Structure
4-(4-pentylphenyl)benzonitrile	C18H19N	40817-08-1	
(4-cyano-3-fluorophenyl) 4-pentylbenzoate	C19H18FNO2	86786-89-2	
1,2,3-trifluoro-5-[4-(4-propylcyclohexyl)cyclohexyl]benzene	C21H29F3	131819-23-3	

1-ethoxy-4-[2-(4-propylphenyl)ethynyl]benzene	C19H20O	39969-29-4	
1-ethoxy-2,3-difluoro-4-[4-(4-propylcyclohexyl)phenyl]benzene	C23H28F2O	189750-98-9	
E7 (commercial mixture): 4-(4-pentylphenyl)benzonitrile (51%) 4-(4-heptylphenyl)benzonitrile (25%) 4-(4-octoxyphenyl)benzonitrile (16%) 4-[4-(4-pentylphenyl)phenyl]benzonitrile (8%)	C18H19N C20H23N C21H25NO C24H23N	63748-28-7	   

2.4. Abbreviation of LCM nomenclature

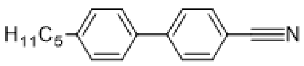
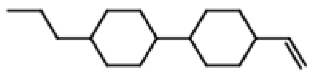
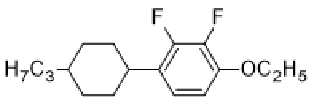
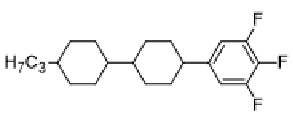
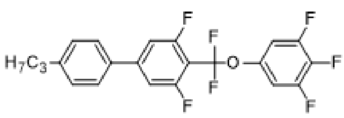
Commercial LCMs used in LCDs can be roughly grouped into three categories according to their structures and functional groups: biphenyls and analogues (BAs), cyanobiphenyls and analogues (CBAs), and fluorinated biphenyls and analogues (FBAs), although some structures are difficult to be grouped into these specific categories (Liang et al., 2021). Due to the large number of compounds that can be used as LCMs, reporting identified analogues by their IUPAC names is not practical due to long names. Therefore, reports on the environmental occurrence of individual LCMs should preferably be in an abbreviated form to facilitate communication of results. However, due to the heterogeneous structural composition of LCMs, with numerous combinations, it is currently difficult to provide a short and accurate acronym system for these compounds. Su et al. (2019), that reported the first environmental contamination of LCMs, used an arbitrarily numbered list of included LCMs; e.g LCM-1, LCM-2,.., LCM-362. However, due to the unsystematic character of this numbering, follow-up studies proposed other ways to systematize the naming convention. In another study, Su et al. (2021) proposed a systematic naming rule for LCMs by abbreviating the different end terminal and core components. The group also provided a comprehensive list of 1173 LCMs with abbreviation according to their acronym system (Su et al., 2022). Furthermore, another group from China also provided their naming system for target LCMs in their papers, although no explanation was provided on which systematic rule the acronyms were based upon (Zhu et al., 2021, Liang et al., 2021). An alternative naming convention can be found in a patent application by Hattori and Saigusa (2013) as well as by Feng et al. (2021), which provides more systematic and informative description of the structure. Table 2 shows the differences in abbreviations between the different studies for the same subcomponent of LCMs.

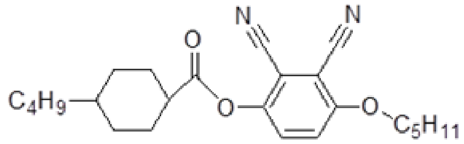
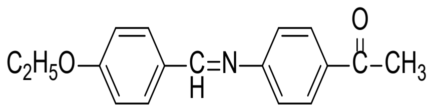
Table 2. Different abbreviations for selected terminal and core groups of LCMs.

Functional group	(Su et al., 2021, Su et al., 2022)	(Zhu et al., 2021)	Modified from (Hattori and Saigusa, 2013) and (Feng et al., 2021)
Methyl (CH_3)	Me	M	1
Pentyl (C_5H_{11})	5	Pe	5
Difluoro Methyl (CHF_2)	CF2		1(F2)
Fluorophenyl (lateral substituted)			G
Difluorophenyl (meta-)	dFP		U
Difluorophenyl (ortho-)	dFP		W
Trifluorophenyl			UF
Cyano (CN)	C	C	C
Vinyl ($CH=CH_2$)	V	V	V
Benzyl	B	B	B
Cyclohexyl	cH		H
Ester/Carboxylic acid (COO)	CaA		E
Ketone (C=O)	Ac		K

Hattori and Saigusa (2013) used abbreviation for each subcomponent of the structure which was written from the left terminal group to the core and right end terminal. A suggestion is made in this current report with a modification of the naming convention by Hattori and Saigusa (2013), which starts by abbreviating the left terminal group (which is the group perceived to be the least polar terminal group) and continue with abbreviating the core group and lastly with the right terminal group (the most polar among the terminal groups). Additional acronyms for common functional groups were provided by Feng et al. (2021) which used a similar system. In cases with two alkyl end groups, the longer chain length should be the left terminal group and named first. Parenthesis is used to indicate additional atoms attached to functional groups. Numbers outside of parenthesis indicate the alkyl chain length. The list of abbreviations using this naming convention for several LCMs can be found in Table 3 together with the abbreviations used by the other research groups for comparison.

Table 3. Chemical structures, IUPAC names, CAS numbers and proposed acronyms for some LCMs.

IUPAC name CAS Structure	Su et al. (2021), (Su et al., 2022)	(Zhu et al., 2021, Liang et al., 2021)	Modified from (Hattori and Saigusa, 2013) and (Feng et al., 2021)
4-(4-pentylphenyl)benzonitrile CAS: 40817-08-1 	5CB	5CB	5BBC
1-ethenyl-4-(4-propylcyclohexyl)cyclohexane CAS: 116020-44-1 	3VbcH	PVB	3HHV
1-ethoxy-2,3-difluoro-4-(4-propylcyclohexyl)benzene CAS: 174350-05-1 	2O3cHdFP	EDPrB	3HWO2
1,2,3-trifluoro-5-[4-(4-propylcyclohexyl)cyclohexyl]benzene CAS: 131819-23-3 	3bcHtFP	TPrCB	3HHUF
2-[difluoro-(3,4,5-trifluorophenoxy)methyl]-1,3-difluoro-5-(4-propylphenyl)benzene CAS: 303186-20-1 	tFPO-CF2-dF3B	DTMDPB	3BU1(F2)OUF
(2,3-dicyano-4-pentoxyphenyl) 4-butylcyclohexane-1-carboxylate CAS: 0075941-51-4	4cHCaA5OdCP	-	4HEB(C2)O5

			
1-[4-[(4-ethoxyphenyl)methylideneamino]phenyl]ethenone CAS: 17224-17-8 	AcPi2OP	-	2OBCBK1

This suggested naming convention is far from complete and can become long for more complex structures, as well as difficult to distinguish between analogue groups. Therefore, further standardization effort is needed to harmonize result reporting and avoid confusion, thus facilitating comparison of identified LCMs between studies.

2.5. Physical-chemical properties and toxicity of LCMs

The potential environmental concerns of LCMs were raised by Li et al. (2018) which screened a list of >300 LCMs for their potential persistent (P), bioaccumulation (B) and toxic (T) properties using predictive models. They found that 87 of screened LCMs had P&B characteristics and mixtures of LCMs extracted from LCD panels of smartphones showed *in vitro* toxicity (Su et al., 2019). Especially, these studies showed that fluorinated LCMs might be of higher environmental concern than the non-fluorinated analogues. Furthermore, the list of screened LCMs were extended to 1173 in a suspect screening study with additional predicted physical-chemical properties (Su et al., 2022). Additionally, atmospheric half-lives were derived using quantum chemical calculations 4-cyanophenyl 4-ethylbenzoate (2BEBC, CAS 56131-48-7), 4-cyano-3-fluorophenyl 4-ethylbenzoate (2BEGC, CAS: 86776-50-3) and 4-cyano-3,5-difluorophenyl 4-ethylbenzoate (2BEUC, CAS 337367-01-8) at 25°C were in the range of 5.7–8.9 days, which suggest that these LCMs can have atmospheric persistence and long-range transport potential (Li et al., 2021). Besides *in silico* models, an increasing number of experimental data has become available regarding various physical-chemical properties of LCMs. For example, the atmospheric lifetimes of two particle-associated LCMs, 1-ethyl-4-(4-(4-propylcyclohexyl)phenyl)benzene (3CBB2, CAS 84540-37-4) and 4''-ethyl-2'-fluoro-4-propyl-1,1':4',1''-terphenyl (3BGB2, CAS 95759-44-7), were found to be up to 25 and 38 days, and were much higher than other organic pollutants such as organophosphate esters and brominated flame retardants (Liu et al., 2020). Feng et al. (2021) used the retention time in GC to experimentally predict the log Koa values of 116 LCMs, which could be useful to prioritize specific LCMs for their persistency and long-range transport characteristics. Also, Zhu et al. (2022) used the shake-flask method to experimentally derive the log K_{ow} values which were in the range of 4.97 to 7.62 for measured LCMs (n=36). These studies suggest that many LCMs have the characteristic properties of persistent organic pollutants.

The tissue-specific bioaccumulation potential in adult zebrafish was studied for 39 LCMs and nine of these showed bioconcentration factors above 1000 (Bao et al., 2023). Most LCMs had similar tissue distribution pattern with levels in intestine > brain > gill > liver > muscle. The low depuration rates, with half-life ranging 1.12 – 7.35 days, further indicate high bioaccumulation and persistency in organisms. Additionally, Wang et al. (2022) studied the biotransformation products and toxicity of EDPrB (See Table 3 for more acronyms). They found around 20 transformation products from different *in vitro* models of human, rat, pig and fish liver microsomes. Additionally, many of these were also found in Sprague-Dawley rats exposed to EDPrB and prediction models showed that some transformation products could have higher toxicity than the parent compound.

2.6. Emission and environmental release of LCMs

The global production capacity of LCD panels was around 300 million m^2 in 2020 according to market reports (DSCC, 2020a). China is currently the market leader with more than two thirds of the market share of LCD panels and the remaining large scale production is situated in Taiwan and South Korea (DSCC, 2020b). In a typical LCD panel, the liquid crystal layer is only a couple of µm thick, and the amount of LCM could be around 0.5-0.6 mg/cm^2 (Li et al., 2018, Cheng et al., 2023).

There are multiple potential sources for the release of LCMs to the environment. These include emission during production, release during use of products containing LCMs and during discard and waste recycling processes. Liu and Abbatt (2021) observed that some tested LCMs could be released from LCD screens which could be a major contribution to the indoor contamination. The emission rates also increased with the increase of relative humidity.

Feng et al. (2022) measured the emission rates of several LCMs from screens removed from obsolete smartphones which ranged 0.002–0.2 $\mu g\ m^{-2}\ h^{-1}$ at 25 °C, which estimated human exposure doses to individual LCMs between 0.0001–2 $ng\ kg^{-1}\ d^{-1}$.

LCD panels have a short lifespan of around 3–8 years and many LCDs are therefore discarded each year (Amato et al., 2017, Ma and Xu, 2013). As such, high levels of LCMs were found from waste LCD panels at a large electronic waste recycling facility in southern China, where Σ_{19}BAs (mean 320-546 $\mu g/cm^2$) and Σ_{39}FBAs (mean 236-242 $\mu g/cm^2$) greatly exceeded those of Σ_6CBAs (low detection frequencies). This shows that recycling of LCM containing products can be a major source of environmental release (Liang et al., 2021). The study provided preliminary estimate on the global release of LCMs from waste television/computer LCD panels to various environmental compartments, which was about 1.07–107 kg/year and will likely increase with time.

Recently, Feng et al. (2023) detected various LCMs in municipal sewage sludge across China, which indicates high potential for release to the environment from these sources.

2.7. Environmental occurrence, distribution and fate of LCMs

Research and monitoring of the environmental levels and distribution of LCMs has just recently begun and therefore very limited information is available at this moment. Mostly research published levels from different levels in China, and thus more studies are needed from other places around the world to investigate the potential widespread occurrences of LCMs in the environment. A table with summary of reported concentrations of LCMs in environmental samples and LCM-containing products can be found in Appendix 1. It should be noted that the sum of LCMs might not be directly compared due to the different number of LCMs measured between the different studies.

2.7.1. Indoor dust and air

Su et al. (2019) was the first to report the presence of LCMs in indoor dust sampled in 2018 in China. They reported that the Σ_{33}LCM concentrations ranged 0.13 – 2213 ng/g among various indoor settings such as residential, teaching, laboratory and hotel buildings in China. Zhang et al. (2022) could detect 14 LCMs in indoor and outdoor dust sampled around different regions of China and the median ΣLCMs was 41.6 ng/g for general indoor dwellings and 94.7 ng/g in outdoor dust, while somewhat higher levels were found for cybercafés (106 ng/g) and phone repair stores (171 ng/g). Studies from other countries outside of China are scarce and one study from Sweden mainly found LCM-3 (3HHO1, CAS 97398-80-6) in indoor dust samples (Dubocq et al., 2021).

As previously mentioned, the e-waste recycling processes can lead to the release of LCMs from e.g., LCD panels. Subsequently, high indoor and outdoor dust (median 46100 ng/g and 6950 ng/g), as well as hand and forehead wipes (46100 and 62100 ng/m^2) have been measured in an e-waste recycling facility in central China (Cheng et al., 2022). Shen et al. (2022) also detected high levels of Σ_{93}LCMs in the air (sum of gas and particles 68.8-385 ng/m^3) of an LCD dismantling facility in south China. This was higher than the air concentrations from a reference site outside of the dismantling facility (15-43.4 ng/m^3). The same group also found higher levels of Σ_{34}FBAs in dust at the LCD dismantling line (median 18500 ng/g) compared to non-LCD dismantling lines (median 2300 ng/g) (Zhu et al., 2021).

2.7.2. Soil and sediment

Li et al. (2023) found LCMs in most sampled soils from different settings such as agricultural, industrial and residential areas. The dominant LCMs were 3cH2B (aka 3HBB2) and 5bcHdFB (aka 5HHBU). Somewhat higher levels were found in agricultural and commercial sites, but individual variations were great among the settings. Sediment concentrations in rivers around LCM or LCD manufacturing sites showed higher concentrations of ΣLCMs (mean 26.1 ng/g) than those in an e-waste recycling area (mean 1.15 ng/g) and lowest levels were found in Lake Taihu (mean 0.076 ng/g) (Su et al., 2021). In a recent study, Tao et al. (2022) collected marine sediment samples around 45 sites at the Pearl River Estuary and detected 10 LCMs with a mean concentration of 36.1 (range 2.1 – 136 ng/g).

2.7.3. Humans and biota levels

Only a few reports have studied biota and human levels of LCMs. Cheng et al. (2022) found LCMs on hand and forehead wipes of workers at an e-waste recycling industrial park in China which indicated potential human exposure in occupational settings. Additionally, 29 LCMs were detected in serum samples from e-waste dismantling workers (median 35.2 ng/mL), with fluorinated analogues as the dominating LCMs (Li et al., 2022). There was also a positive correlation between levels of fluorinated LCMs in paired indoor dust and human breast milk collected from Beijing in 2020-2021 (Yang et al., 2023).

A new study showed that some LCMs could be found in marine biota such as fish and crab at a coastal bay around the south of China. Besides LCMs, the study also included some other organic light-emitting materials (OLEMs) that are used in OLED panels and might also be persistent int the environment. Higher levels of ΣOLEMs (incl LCMs) were found in fish such as grunt (mean 9.9 ng/g ww) and mackerel (mean 9.46 ng/g ww) as well as claw crab (2.47 ng/g ww).

2.8. Outlook

More evidence from theoretical studies and laboratory experiments have shown that many LCMs are persistent, bioaccumulative and potentially toxic. Due to the high production and use volumes of LCMs, it is also expected that the LCMs can be released to the environment during production, use of associated products (e.g., LCD screens) and disposal or recycling of LCM containing products. Almost all environmental monitoring studies on LCMs were conducted in China, where high detection rates were found which indicates contamination around point source regions in China. However, the extent of global contamination is currently unknown as there are almost no reports on LCMs from other countries at the moment. Therefore, it is recommended that more studies be conducted from other regions, from e.g., indoor environments or electronic recycling facilities for preliminary screening purposes. Additionally, OLEMs have similar structure to LCMs with aromatic core structures. Their production volumes have been increasing rapidly in recent years due to the increasing demand for organic light-emitting diode (OLED) panels. Subsequently, potential environmental contamination of OLEMs should be monitored.

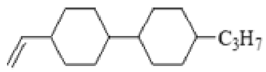
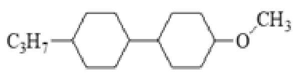
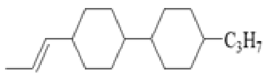
3. Pilot study on LCMs in sewage sludge

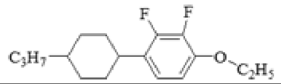
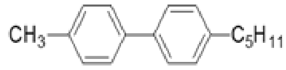
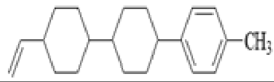
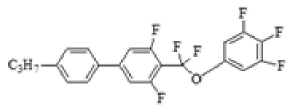
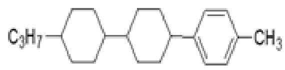
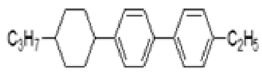
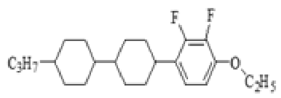
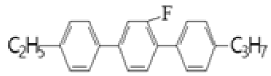
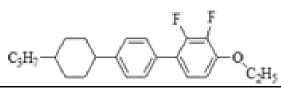
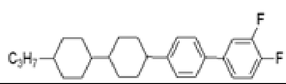
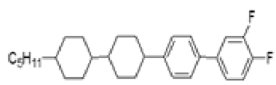
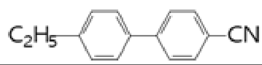
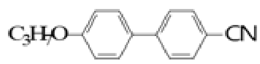
In view of the global contamination potential of LCMs, a method development was carried out to investigate the occurrence of selected LCMs in wastewater sludge samples. Three wastewater sludge samples (A1, A7, A9) collected around Sweden in 2016 and stored in -20°C were used in this project for the analytical method development and screening of selected LCMs.

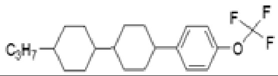
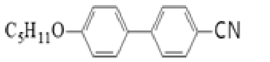
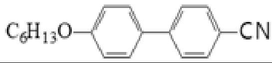
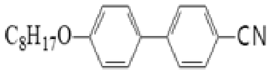
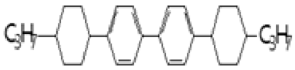
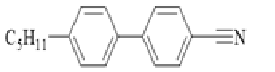
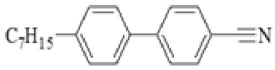
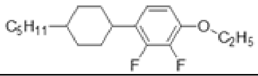
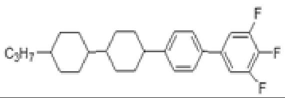
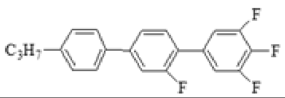
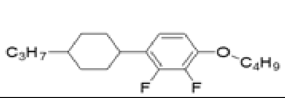
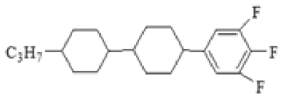
3.1. Target LCMs

A total of 28 LCMs were included in this pilot study and these are outlined in Table 4. These were purchased from TCI Europe (purity ≥98%).

Table 4. List of LCMs included in this method development pilot study.

Abbreviation (this study)	**Abbreviation (Su et al, 2022)**	**CAS**	**Formula**	**Mono-isotopic mass**	**Structure**
3HHV	3VbcH	116020-44-1	C17H30	234.2348	
3HHO3	MeO3bcH	97398-80-6	C16H30O	238.2297	
3HHV1	Pe3bcH	279246-65-0	C18H32	248.2504	

3HWO2	2O3cHdFP	174350-05-1	C17H24F2O	282.1795	
5BB1	5MeB	64835-63-8	C18H22	238.1722	
VHHB1	MePVbcH	155041-85-3	C21H30	282.23475	
3BU1(F2)OUF	tFPO-CF2-dF3B	303186-20-1	C22H15F7O	428.1011	
3HHB1	MeP3bcH	84656-75-7	C22H34	298.2661	
3HBB2	3cH2B	84540-37-4	C23H30	306.2348	
3HHWO2	2OdFP3bcH	123560-48-5	C23H34F2O	364.2578	
3BGB2	2F3T	95759-44-7	C23H23F	318.1784	
3HBWO2	2O3cHdFB	189750-98-9	C23H28F2O	358.2108	
3HHBU	3bcHdFB	119990-81-7	C27H34F2	396.2629	
5HHBU	5bcHdFB	136609-96-6	C29H38F2	424.2942	
2BBC	2CB	58743-75-2	C15H13N	207.1048	
3OBBC	3OCB	52709-86-1	C16H15NO	237.1154	

3HHBO1(3F)	tFMeO 3bcHP	133937-72-1	C22H31F3O	368.2327	
5OBBC	5OCB	52364-71-3	C18H19NO	265.1467	
6OBBC	6OCB	41424-11-7	C19H21NO	279.1623	
8OBBC	8OCB	52364-73-5	C21H25NO	307.1936	
3HBBH3	b3cHB	85600-56-2	C30H42	402.3287	
5BBC	5CB	40817-08-1	C18H19N	249.1518	
7BBC	7CB	41122-71-8	C20H23N	277.1831	
5HWO2	5cH2OdFP	124729-02-8	C19H28F2O	310.2108	
3HHBUF	3bcHtFB	137529-41-0	C27H33F3	414.2534	
3BGUF	3teFT	205806-87-7	C21H16F4	344.1188	
3HWO4	3cH4OdFP	208709-55-1	C19H28F2O	310.2108	
3HHUF	3bcHtFP	131819-23-3	C21H29F3	338.2221	

3.2. Extraction and clean-up procedures

Since no isotopically labelled LCMs are commercially available, previous studies used isotopically labelled standards of structurally similar compounds, including ^{13}C-labelled PCBs as internal standards (Cheng et al., 2022, Su et al., 2021, Li et al., 2023, Bao et al., 2023). In this current pilot study, a method originally validated for PCBs was tested for the sample extraction and pretreatment of the target LCMs. The frozen sludge samples were thawed, freeze-dried and then homogenized using ceramic mortar and pestle. An aliquot of the sample (0.2 g) was mixed with 35 g of anhydrous sodium sulfate (Na_2SO_4) and spiked with PCB surrogate standard. The mixture was thereafter extracted using accelerated solvent extraction (ASE 350, Thermo Scientific Dionex). The ASE cell was fitted (from the bottom up) with a cellulose filter, then filled with activated copper powder, sample homogenate, anhydrous sodium sulfate (approx. 1 cm from the top) and lastly fitted with another cellulose filter. The extraction solvent consists of n-hexane:DCM (1:1, v/v) and the extraction cycle was as follows: 5 min static in three cycles, temperature at 100 °C, pressure at 1500 psi, flush volume at 60%, nitrogen purge for 120 seconds. The extract was evaporated to 1 mL and then cleaned-up using a multilayer column consisting of (from the bottom up) 1 g Na_2SO_4, 8 g activated silica, 4 g 5% deactivated alumina, and 1 g Na_2SO_4. The column was precleaned using 100 mL n-hexane:DCM (1:1) and then the extract was loaded. The analytes were eluted with 200 mL of n-hexane:DCM (1:1). Finally, the eluent was rotary evaporated to 1 mL, filtered through a 0.45 µm filter, nitrogen evaporated to near dryness, reconstituted with n-hexane and then spiked with ^{13}C-PCB volumetric standards.

3.3. Instrumental analysis

Instrumental analysis was carried out using a gas chromatograph coupled with orbitrap high resolution mass spectrometer (GC-orbitrap HRMS, Q-Exactive, Thermo Scientific). The injector temperature was held at 280 °C, and 1 µL of the extract was injected in splitless mode into a DB5-MS column (L 30 m, ID 0.25 mm, stationary phase 0.25 µm). The GC oven temperature program was as follows: initial temperature 70 °C, ramp 8 °C/min to 205 °C, ramp 4 °C/min to 320 °C, hold 6 min. The MS transfer line temperature was 280 °C and ion source temperature was 250 °C. An initial method using full scan mode (m/z 50-550, mass resolution of 60 000 FWHM) was tested. However, due to substantial matrix interference in the sludge samples, a second method using a targeted-SIM approach was set up. In this mode, specific mass-over-charge (m/z) for the analytes and internal standards were isolated within a 4.0 m/z range at different chromatographic time windows in the quadrupole before entering the orbitrap. The mass resolution was set to 30 000 FWHM. This method should remove a major part of the matrix ions and allow more target ions to be sent to the analyzer. The following results and discussions were made based on the targeted-SIM method.

3.4. Discussion of the analytical results

Procedural blanks, solvent blanks and spiked replicates were included during the method testing procedure. A seven-point calibration curve ranged 0.5-1000 pg/uL showed high linearity with R^2 >0.99 for all LCMs. The instrument limits of detection (IDL) were estimated to be around 0.1-5 pg/uL for the different LCMs based on the peak responses and signal-to-noise ratio of the calibration standards. However, it should be noted that the IDLs for orbitrap instruments can vary significantly between standards and samples with complex matrices (Kaufmann, 2018).

A spiked recovery experiment was conducted using a test sludge sample (A7). Three aliquots (amount: 0.2 g, n=3) were spiked before extraction with 1000 pg of native LCMs and underwent the described sample processing method in section 3.2 (sample code prefix SS). Recoveries of surrogate ^{13}C-PCB in all spiked samples were between 27% to 134% (average 66-104%), indicating an acceptable range for PCBs. However, the spiked recoveries of native LCMs were very low. As can be seen in Table 5, the amounts recovered in the spiked sludge samples (SS-1, SS-2, SS-3) were far less than the 1000 pg spiking level, and some LCMs were even undetected. Furthermore, the spiked procedural blank (SS-B) also recovered only a small portion of LCMs which indicated that the sample pretreatment steps, although suitable for PCBs, were not suitable for LCMs.

To investigate the matrix effect, another triplicate of the test sludge (A7) underwent the same sample pretreatment and but were instead spiked with native LCMs in the final extract before instrumental analysis (sample prefix ES). As can be seen, strong matrix suppression could be found for most analytes, such as 3HHV and 3HHV1 that remained undetected in the spiked extracts.

Table 5. Amounts of LCMs (in pg) measured in procedural blank (PB), sludge samples (A1, A7, A9), spiked sludge before extraction (SS) and spiked sludge after extraction and pretreatment (ES). The spiking amount was 1000 pg of target LCMs for all spiked samples.

LCM	PB	A1	A7	A9	SS-B	SS-1	SS-2	SS-3	ES-B	ES-1	ES-2	ES-3
3HHV	0	0	0	0	325	0	0	0	757	0	0	0
3HHO3	0	0	0	0	463	403	245	707	761	1032	1250	1249
3HHV1	0	0	0	0	0	0	0	0	543	0	0	0
3HWO2	58	59	52	61	132	174	107	213	590	884	1038	895
2BBC	0	0	0	0	32	36	0	25	624	590	657	600
5BB1	0	0	0	0	48	41	7	37	585	474	514	459
5HWO2	0	0	0	0	84	279	23	71	711	437	477	426
3HWO4	0	0	0	0	55	53	17	54	638	599	621	626
3OBBC	0	0	0	0	30	27	28	30	669	549	562	549
5BBC	0	0	0	0	67	58	31	58	601	586	571	580
3HHBO1(3F)	0	0	0	0	58	47	19	48	749	573	568	529
3HHUF	0	0	0	0	27	22	11	37	592	559	664	615
VHHB1	0	0	0	0	159	0	0	0	760	815	809	871
3BU1(F2)OUF	0	0	0	0	59	72	21	96	565	804	906	938
3BGUF	0	0	0	0	49	56	20	65	677	656	795	733
5OBBC	0	0	0	0	112	0	103	123	655	706	736	714
3HHB1	0	0	0	0	172	1112	852	981	682	1434	1248	1127
7BBC	0	0	0	0	146	137	117	140	661	690	708	685
6OBBC	0	0	0	0	139	109	176	280	450	1170	1483	1240
3HBB2	0	0	0	0	91	133	64	146	635	1054	1192	1208
3HHWO2	0	0	0	0	73	72	40	85	651	644	701	698
3BGB2	25	25	25	25	69	91	43	114	560	885	1059	1071
3HBWO2	0	0	0	0	102	82	64	113	653	787	868	717
8OBBC	0	0	0	0	86	67	63	98	476	623	721	550
3HHBUF	0	0	0	0	37	30	5	35	580	488	509	496
3HHBU	0	0	0	0	0	0	0	0	568	443	490	487
5HHBU	0	0	0	0	33	19	0	19	681	499	496	491
3HBBH3	0	0	0	0	21	24	37	39	485	543	617	620

These results indicate that the sample pretreatment was not sufficient to extract and elute the LCMs, and together with the strong matrix effect, prevented an efficient analysis of LCMs. The reason for this is currently unclear. Similar extraction and clean-up methods have been published in previous studies for other solid matrices (Su et al., 2021, Li et al., 2023) as well as in sewage sludge (Feng et al., 2023). These studies mainly used GC-MS/MS for quantification, which might be more efficient, compared to the GC orbitrap HRMS, in reducing matrix effects from complex solid samples. However, it is clear from the results that the sample extraction and clean-up need to be further optimized to elute the LCM target compounds more efficiently.

Based on the current method, LCMs in the three collected sludge samples could not be measured above the method detection limits and procedural blanks. However, as stated above, the analytical method is not currently optimized for LCMs and a clear conclusion can therefore not be made regarding the presence or absence of LCMs in the Swedish sludge samples.

4. Conclusions and suggested future works

A literature review was conducted regarding the emerging environmental contamination of liquid crystal monomers. The surveyed studies suggested that LCMs can be emitted from electronic displays to the surrounding environment. Furthermore, LCMs might also be released from manufacturing point sources as well as from e-waste dismantling processes. The current studies reported widespread detection of LCMs in most environmental compartments in China. However, more monitoring studies are needed from other countries to assess the global contamination potential of LCMs. Additionally, a common acronym system is needed to be able to report and compare levels of different LCMs. Finally, more reliable analysis methods are needed to unequivocally detect and reliably detect LCMs in complex environmental matrices such as sewage sludge.

5. Acknowledgements

We would like to thank Maria Larsson and Anna Kärrman at Örebro University for their support and discussions during the project. We would also like to thank Yanfen Hao, Jing Xu and Pu Wang at Jianghan University, Wuhan, China for the technical assistance regarding the chemical analysis. Karl Lilja and Linda Linderholm are acknowledged for their great support.

9. References

AMATO, A., ROCCHETTI, L. & BEOLCHINI, F. 2017. Environmental impact assessment of different end-of-life LCD management strategies. *Waste Management,* 59**,** 432-441.

BAO, Y., ZHU, M. & SU, G. 2023. Tissue-specific accumulation, bioaccumulation, and depuration of liquid crystal monomers (LCMs) in adult zebrafish (Danio rerio). *Science of The Total Environment,* 859**,** 160267.

CASTELLANO, J. A. 2005. *Liquid Gold: The Story Of Liquid Crystal Displays And The Creation Of An Industry,* Singapore, SINGAPORE, World Scientific Publishing Company.

CHENG, Z., SHI, Q., WANG, Y., ZHAO, L., LI, X., SUN, Z., LU, Y., LIU, N., SU, G., WANG, L. & SUN, H. 2022. Electronic-Waste-Driven Pollution of Liquid Crystal Monomers: Environmental Occurrence and Human Exposure in Recycling Industrial Parks. *Environmental Science & Technology,* 56**,** 2248-2257.

CHENG, Z., ZHANG, S., SU, H., ZHAO, H., SU, G., FANG, M. & WANG, L. 2023. Emerging organic contaminants of liquid crystal monomers: Environmental occurrence, recycling and removal technologies, toxicities and health risks. *Eco-Environment & Health,* 2**,** 131-141.

DSCC. 2020a. *Display panel production capacity from 2016 to 2025, by type (in million square meters) [Graph]. In Statista* [Online]. Available: https://www.statista.com/statistics/1057441/display-panel-production-capacity-type/ [Accessed August 23, 2022].

DSCC. 2020b. *LCD panel production capacity share from 2016 to 2025, by country [Graph]. In Statista.* [Online]. Available: https://www.statista.com/statistics/1056470/lcd-panel-production-capacity-country/ [Accessed August 26, 2022].

DUBOCQ, F., KÄRRMAN, A., GUSTAVSSON, J. & WANG, T. 2021. Comprehensive chemical characterization of indoor dust by target, suspect screening and nontarget analysis using LC-HRMS and GC-HRMS. *Environmental Pollution,* 276**,** 116701.

FENG, J.-J., SUN, X.-F. & ZENG, E. Y. 2021. Measurement of octanol–air partition coefficients for liquid crystals based on gas chromatography-retention time and its implication in predicting long-range transport potential. *Chemosphere,* 282**,** 131109.

FENG, J.-J., SUN, X.-F. & ZENG, E. Y. 2022. Emissions of Liquid Crystal Monomers from Obsolete Smartphone Screens in Indoor Settings: Characteristics and Human Exposure Risk. *Environmental Science & Technology,* 56**,** 8053-8060.

FENG, Z., DU, B., SHEN, M., HAN, X., LIANG, X. & ZENG, L. 2023. Nationwide occurrence and distribution of liquid crystal monomers in municipal sewage sludge of China. *Science of The Total Environment***,** 164453.

HATTORI, N. & SAIGUSA, K. 2013. *LIQUID CRYSTAL COMPOSITION AND LIQUID CRYSTAL DISPLAY DEVICE*. Japan patent application US 2013/0062560 A1.

HIRD, M., GOODBY, J. W., LEWIS, R. A. & TOYNE, K. J. 2003. THE FASCINATING INFLUENCE OF FLUORO SUBSTITUENTS ON THE SYNTHESIS AND PROPERTIES OF LIQUID CRYSTALS. *Molecular Crystals and Liquid Crystals,* 401**,** 1-18.

HIRD, M. & TOYNE, K. J. 1998. Fluoro Substitution in Thermotropic Liquid Crystals. *Molecular Crystals and Liquid Crystals Science and Technology. Section A. Molecular Crystals and Liquid Crystals,* 323**,** 1-67.

JAIN, A. K. & DESHMUKH, R. R. 2020. An Overview of Polymer-Dispersed Liquid Crystals Composite Films and Their Applications. *In:* GHAMSARI, M. S. & CARLESCU, I. (eds.) *Liquid Crystals and Display Technology.* IntechOpen.

JONES, J. C. 2018. Liquid crystal displays. *In:* DAKIN, J. P. & BROWN, R. G. W. (eds.) *Handbook of Optoelectronics: Enabling Technologies.* Boca Raton, FL, USA: CRC Press.

KAUFMANN, A. 2018. Analytical performance of the various acquisition modes in Orbitrap MS and MS/MS. *Journal of Mass Spectrometry,* 53**,** 725-738.

KIM, K.-H. & SONG, J.-K. 2009. Technical evolution of liquid crystal displays. *NPG Asia Materials,* 1**,** 29-36.
KLASEN-MEMMER, M. & HIRSCHMANN, H. 2012. Liquid Crystal Materials for Devices. *In:* CHEN, J., CRANTON, W. & FIHN, M. (eds.) *Handbook of Visual Display Technology.* Berlin, Heidelberg: Springer Berlin Heidelberg.
LI, C., HUANG, Y., ZHANG, X., ZHAO, Y. & HUO, Y. 2021. Atmospheric Fate and Risk Investigation of Typical Liquid Crystal Monomers. *ACS Sustainable Chemistry & Engineering,* 9**,** 3600-3607.
LI, J., SU, G., LETCHER, R. J., XU, W., YANG, M. & ZHANG, Y. 2018. Liquid Crystal Monomers (LCMs): A New Generation of Persistent Bioaccumulative and Toxic (PBT) Compounds? *Environmental Science & Technology,* 52**,** 5005-5006.
LI, R., REN, K., SU, H., WEI, Y. & SU, G. 2023. Target and suspect analysis of liquid crystal monomers in soil from different urban functional zones. *Science of The Total Environment,* 854**,** 158408.
LI, Y., ZHANG, T., CHENG, Z., ZHANG, Q., YANG, M., ZHAO, L., ZHANG, S., LU, Y., SUN, H. & WANG, L. 2022. Direct evidence on occurrence of emerging liquid crystal monomers in human serum from E-waste dismantling workers: Implication for intake assessment. *Environment International,* 169**,** 107535.
LIANG, X., XIE, R., ZHU, C., CHEN, H., SHEN, M., LI, Q., DU, B., LUO, D. & ZENG, L. 2021. Comprehensive Identification of Liquid Crystal Monomers—Biphenyls, Cyanobiphenyls, Fluorinated Biphenyls, and their Analogues—in Waste LCD Panels and the First Estimate of their Global Release into the Environment. *Environmental Science & Technology,* 55**,** 12424-12436.
LIU, Q. & ABBATT, J. P. D. 2021. Liquid crystal display screens as a source for indoor volatile organic compounds. *Proceedings of the National Academy of Sciences,* 118**,** e2105067118.
LIU, Q., LIGGIO, J., WENTZELL, J., LEE, P., LI, K. & LI, S.-M. 2020. Atmospheric OH Oxidation Chemistry of Particulate Liquid Crystal Monomers: An Emerging Persistent Organic Pollutant in Air. *Environmental Science & Technology Letters,* 7**,** 646-652.
LORCH, M. 2022. *The chemistry behind your LCD flat-screen devices: how a scientist changed the world* [Online]. Available: https://theconversation.com/the-chemistry-behind-your-lcd-flat-screen-devices-how-a-scientist-changed-the-world-176936 [Accessed 2022-08-10].
MA, E. & XU, Z. 2013. Technological process and optimum design of organic materials vacuum pyrolysis and indium chlorinated separation from waste liquid crystal display panels. *Journal of Hazardous Materials,* 263**,** 610-617.
SARGAZI, M., LINFORD, M. R. & KAYKHAII, M. 2019. Liquid Crystals in Analytical Chemistry: A Review. *Critical Reviews in Analytical Chemistry,* 49**,** 243-255.
SHEN, M., FENG, Z., LIANG, X., CHEN, H., ZHU, C., DU, B., LI, Q. & ZENG, L. 2022. Release and Gas–Particle Partitioning Behavior of Liquid Crystal Monomers during the Dismantling of Waste Liquid Crystal Display Panels in E-Waste Recycling Facilities. *Environmental Science & Technology,* 56**,** 3106-3116.
SU, H., REN, K., LI, R., LI, J., GAO, Z., HU, G., FU, P. & SU, G. 2022. Suspect Screening of Liquid Crystal Monomers (LCMs) in Sediment Using an Established Database Covering 1173 LCMs. *Environmental Science & Technology,* 56**,** 8061-8070.
SU, H., SHI, S., ZHU, M., CRUMP, D., LETCHER, R. J., GIESY, J. P. & SU, G. 2019. Persistent, bioaccumulative, and toxic properties of liquid crystal monomers and their detection in indoor residential dust. *Proceedings of the National Academy of Sciences,* 116**,** 26450-26458.
SU, H., SHI, S., ZHU, M., LI, J. & SU, G. 2021. Liquid Crystal Monomers (LCMs) in Sediments: Method Validation and Detection in Sediment Samples from Three Typical Areas. *Environmental Science & Technology,* 55**,** 2336-2345.

TAO, D., JIN, Q., RUAN, Y., ZHANG, K., JIN, L., ZHAN, Y., SU, G., WU, J., LEUNG, K. M. Y., LAM, P. K. S. & HE, Y. 2022. Widespread occurrence of emerging E-waste contaminants – Liquid crystal monomers in sediments of the Pearl River Estuary, China. *Journal of Hazardous Materials,* 437**,** 129377.

WANG, X., YANG, R., ZHANG, J., CHEN, X., FENG, Y., NIU, Y. & SHAO, B. 2022. Metabolic profiling of the fluorinated liquid-crystal monomer 1-ethoxy-2,3-difluoro-4-(trans-4-propylcyclohexyl)benzene. *Sci Total Environ*.

WU, S.-T., YANG, D.-K. & WU, S.-T. 2014. *Fundamentals of Liquid Crystal Devices,* New York, UNITED KINGDOM, John Wiley & Sons, Incorporated.

YANG, D.-K. & WU, S.-T. 2015. *Fundamentals of liquid crystal devices,* Chichester, England, Wiley.

YANG, R., WANG, X., NIU, Y., CHEN, X. & SHAO, B. 2023. Fluorinated Liquid-Crystal Monomers in Paired Breast Milk and Indoor Dust: A Pilot Prospective Study. *Environment International,* 176**,** 107993.

ZHANG, S., YANG, M., LI, Y., WANG, Y., LU, Y., CHENG, Z. & SUN, H. 2022. Occurrence, Distribution, and Human Exposure of Emerging Liquid Crystal Monomers (LCMs) in Indoor and Outdoor Dust: A Nationwide Study. *Environment International,* 164**,** 107295.

ZHU, M., SHEN, M., LIANG, X., CHEN, H., ZHU, C., DU, B., LUO, D., LAN, S., FENG, Z. & ZENG, L. 2021. Identification of Environmental Liquid-Crystal Monomers: A Class of New Persistent Organic Pollutants—Fluorinated Biphenyls and Analogues—Emitted from E-Waste Dismantling. *Environmental Science & Technology,* 55**,** 5984-5992.

ZHU, M., SU, H., BAO, Y., LI, J. & SU, G. 2022. Experimental determination of octanol-water partition coefficient (KOW) of 39 liquid crystal monomers (LCMs) by use of the shake-flask method. *Chemosphere,* 287**,** 132407.

Appendix 1

Table A1. Summary of ΣLCM levels reported for environmental samples and various products in published studies.

						Number of LCMs			ΣLCM			
Matrix	Country	Site	Settings/ Type	Sampling Year	Samples (n)	Measured	Detected	Unit	Mean	Median	Range	Ref
Air Indoor Gas	China	South China	E-waste LCM dismantling	2020	32	93	53	ng/m3		150	66.2 - 243	10
Air Indoor Particulate	China	South China	E-waste LCM dismantling	2020	32	93	53	ng/m3		46.9	2.69 - 142	10
Air Outdoor Gas	China	South China	E-waste reference	2020	4	93		ng/m3		21.7	14-37.6	10
Air Outdoor Particulate	China	South China	E-waste reference	2020	4	93		ng/m3		2.96	0.91-6.34	10
Biota Fish	China	South China	Coast	NA	54	30 (LCMs+OLEMs)	29 (LCMs+OLEMs)	ng/g		9.5	ND - 29.7	11
Biota Invertebrate	China	South China	Coast	NA	38	30 (LCMs+OLEMs)	29 (LCMs+OLEMs)	ng/g		7.36	ND - 7.36	11
Dust Indoor	China	E-waste	Workshop#1	2020	53	55		ng/g	97800	67400	21600 - 354000	1
Dust Indoor	China	E-waste	Workshop#2	2020	23	55		ng/g	12600	11000	4720 - 38300	1
Dust Indoor	China	Reference site	Reference site	2020	30	55		ng/g	399	303	54 - 1050	1
Dust Indoor	Sweden	Örebro	Various	2019	30	12	3	ng/g		195	ND - 1586	4
Dust Indoor	China	Jiangxi	LCD dismantling	2020	31	46	34	ng/g	82000	18500	225 - 976000	7
Dust Indoor	China	Jiangxi	non-LCD dismantling	2020	31	46	34	ng/g	3290	2300	292 - 18500	7
Dust Indoor	China	Nanjing	Various	2018	53	33	17	ng/g			0.13 - 2213	9
Dust Indoor	China	China	Dwellings	2021	48	60	8	ng/g	87.2	41.6	17.3 - 529	12
Dust Indoor	China	China	Cybercafes	2021	34	60	16	ng/g	326	106	4.40-2540	12
Dust Indoor	China	China	Phone repair store	2021	22	60	19	ng/g	240	171	2.37-991	12
Dust Indoor	China	Beijing	Residential	2021	93	39	37	ng/g		12	4.33 - 121.15	14
Dust Outdoor	China	E-waste	E-waste	2020	43	55		ng/g	7310	6950	3450 - 15300	1

Dust Outdoor	China	China	General	2021	97	60	13	ng/g	113	94.7	ND-441	12
Human BreastMilk	China	Beijing	Mothers	2021	93	39	30	ng/g lw		133.4	11.97 - 28200	14
Panel Computer	China	E-waste	Various	2020	80	93	64	ng/cm^2	788000		53500 - 2110000	5
Panel TV	China	E-waste	Various	2020	80	93	64	ng/cm^2	556000		44700 - 1920000	5
Sediment Lake	China	Taihu	Taihu Lake	2019	23	39	28	ng/g	0.076		0.033 - 0.193	8
Sediment Marine	China	Pearl River Estuary	Coastal	2018	45	39	10	ng/g	36.1		2.1 - 136	13
Sediment River	China	Nanjing	LCD manufacturing	2019	30	39	28	ng/g	26.1		0.032 - 554	8
Sediment River	China	Taizhou	E-waste	2019	23	39	28	ng/g	1.15		ND - 3.10	8
Serum	China	E-waste	E-waste worker	2015	85	60	29	ng/mL		35.2	7.8 - 276	2
Serum	China	Reference site	Reference site	2015	16	60	29	ng/mL		9.6	3.2 - 28.5	2
Sludge	China	China	Wastewater treatment plants	2020	101	65	48	ng/g		46.4	17.2 - 225	15
Soil	China	South China	Agricultural	2019	96	39	30	ng/g	12.9	0.64	ND - 250	3
Soil	China	South China	Commercial	2019	96	39	30	ng/g	5.23	0.49	ND - 24	3
Soil	China	South China	Residential	2019	96	39	30	ng/g	3.3	0.63	ND - 7.65	3
Soil	China	South China	Industrial	2019	96	39	30	ng/g	2.48	0.91	ND - 8.73	3
Soil	China	South China	Scenic	2019	96	39	30	ng/g	0.77	0.25	ND - 1.71	3
Water Landfill	China	Hong Kong	Landfill	2021	3	39	30	ng/L			1120	6
Water Landfill	China	Shenzen	Landfill	2021	3	39	30	ng/L			409	6
Wipes	China	Reference site	Reference site	2020	30	55		ng/m2	6030	4160	1350 - 22000	1
Wipes Forehead	China	E-waste	E-waste worker	2020	43	55		ng/m2	244000	62100	13200 - 2071000	1
Wipes Hand	China	E-waste	E-waste worker	2020	43	55		ng/m2	129000	46100	9980 - 1197000	1

1. Cheng et al. Environ Sci Technol. 2022 Feb 15;56(4):2248-2257

2. Li et al. Environment International. Volume 169, November 2022, 10753

3. Li et al. Science of The Total Environment. Volume 854, 1 January 2023, 158408

4. Dubocq et al. Environmental Pollution 276 (2021) 116701.

5. Liang et al. Environ. Sci. Technol. 2021, 55, 12424−12436

6. Jin et al. Journal of Hazardous Materials. Volume 423, Part B, 5 February 2022, 127146
7. Zhu et al. Environ Sci Technol 2021, 55, 9, 5984-5992
8. Su et al. Environ. Sci. Technol. 2021, 55, 2336−2345
9. Su et al. PNAS, 2019, 116, 264540-26458
10. Shen et al. Environ. Sci. Technol. 2022, 56, 3106−3116
11. Wang et al. Environ. Sci. Technol. Lett. 2022, 9, 739−746
12. Zhang et al. Environment International 164 (2022) 107295
13. Tao et al. Journal of Hazardous Materials 437 (2022) 129377
14. Yang et al. Environ Int, 2023, 176, 107993
15. Feng et al. Sci Tot Environ. 2023, 892, 164453