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A Review: Liquid Crystals as a Novel Drug Carrier and Applications with Future Trends

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ABSTRACT: Drug-loaded liquid crystals have emerged as a promising approach for drug delivery with numerous advantages over traditional delivery methods. This review highlights the different types of liquid crystal phases, including lamellar, cubic, and hexagonal phases, and their suitability for drug delivery. The preparation and characterization of drug-loaded liquid crystals are also discussed. The unique structure of liquid crystals allows for controlled drug release, targeted delivery, and improved bioavailability. Several successful drug-loaded liquid crystal formulations have been reported, demonstrating their potential as an effective drug delivery system. However, there is still ample room for future research to optimize drug loading and release, explore the potential of new types of liquid crystal phases, and investigate the feasibility of liquid crystal-based drug delivery for different routes of administration. Overall, drug-loaded liquid crystals hold great promise as a novel drug delivery system, and continued research in this field has the potential to significantly advance the field of drug delivery.

KEYWORDS- Liquid crystals, lyotropic liquid crystals, nanoparticles.

INTRODUCTION :

Liquid crystals are a distinct state of matter that exist between a crystalline solid and an isotropic liquid. They possess many of the mechanical features of a liquid, such as high fluidity, inability to resist shear, and the ability to form and merge droplets. However, they also display anisotropic properties in optics, electricity, and magnetism, much like crystals. The term "liquid crystal" was first coined by Lehmann in 1889 to describe this unique state of matter[1].

Liquid crystals are types of fluids in which the constituent molecules are disordered enough to be classified as a liquid and exhibit flow properties, but they also exhibit varying degrees of ordering based on the specific type of liquid crystal phase present[2].
Liquid crystals are used in various applications, including LCDs (liquid crystal displays), thermometers, photoconductor optical imaging, electro-optical devices, and medical equipment[3,4].

Liquid crystals have also been found to have new and innovative applications in analytical chemistry. They are particularly useful in the development of sensors, the analysis of biological materials, and gas chromatography (GC).

Liquid crystals can be categorized based on their characteristics, such as their geometric or architectural structure. They are classified as calamitic or discotic. Calamitic liquid crystals are made up of molecules with a rod-like shape, while discotic liquid crystals are composed of molecules with a disc-like shape. They are further categorized as thermotropic or lyotropic, depending on whether they are formed through thermal means or through the influence of solvents, respectively[5].

The mesophases that form monomer liquid crystals (MLCs) and polymer liquid crystals (PLCs) have long-range order in one or both dimensions, either in terms of the position or the orientation of the molecules. The rigid component responsible for this liquid crystalline behavior is called a mesogen[6].

The molecules that form liquid crystal phases often have specific structural characteristics, which can be described as follows:
(a) The molecules are elongated. Liquid crystallinity is more likely to occur if the molecules have flat segments, e.g., benzene rings.
(b) A fairly rigid backbone containing double bonds defines the long axis of the molecule
(c) The existence of strong dipoles and easily polarizable groups in the molecule seems important. (d) The groups attached to the extremities of the molecules are generally of lesser importance[7].

Types of Liquid Crystals:

Liquid crystals are categorized based on the subatomic structure of their particles, which results in positional and/or orientational order within the lattice. The following are the different categories of liquid crystals:

Thermotropic Liquid Crystal:

The term "thermotropic" refers to liquid crystal molecules that change their shape and properties in response to temperature changes. The word "thermo" refers to temperature, while "tropic" refers to the tendency of the molecules to align in specific ways. When heated, these liquid crystals usually become isotropic liquids, losing their long-range positional and orientational order. Thermotropic liquid crystals are typically categorized into nematic, smectic, and cholesteric phases.

Smectic (Sm) Phase:

In the smectic phase of liquid crystals, the layers are arranged with their long axes perpendicular to the direction of molecular orientation, and the arrangement of the molecules within each layer is visible with distinct interlayer spacing. This phase is further classified into various sub-phases, including smectic A, smectic B, smectic C, and so on, based on the specific arrangement and orientation of the molecules. Some smectic phases, such as smectic C, smectic F, and smectic I, are tilted, while others, such as smectic A and smectic B, are orthogonal or non-tilted[8].

Nematic Phase (N):

The nematic phase of liquid crystals is the simplest and least organized mesophase structure, where the molecules exhibit one-dimensional orientational order, but not positional order. The degree of order in the nematic phase can be measured by an order parameter, S, and the average orientation of the molecules in the phase is described by a "director" parameter, n. The formula is given below[9].

$$S = \frac{1}{2}\left(3\ cos^2\ \theta - 1\right)$$

The order parameter S of a nematic phase is defined as the average value of the cosine squared of the angle (θ) between the long axis of an individual molecule and the director parameter (n) representing the average orientation of molecules in the phase. The value of S for a nematic phase typically falls between 0.4 and 0.7, indicating a moderate degree of orientational order. Because of the parallel alignment of the molecules along their long axes, nematic phases exhibit anisotropy. One of the primary applications of nematic phases is in electronic displays[10].

Cholesteric Phase :

The chiral nematic liquid crystal phase, also known as the cholesteric phase, exhibits a helical structure where the molecules are organized in successive layers. When plane-polarized light interacts with these chiral structures, a rotation of light in the helical direction can be observed. If the pitch of these helical structures falls within the range of 400-800 nm, which is the visible portion of the spectrum of light, the phase appears colored. The pitch of the helix is influenced by temperature, which also affects the wavelength reflected. The ability of the helix to unwind in response to changes in the electric field can be utilized in a stimuli-responsive drug delivery system[11,12].

Lyotropic Liquid Crystals:

To clarify, the word "lyotropic" was derived from the Greek word "lyo," meaning "to dissolve," and "tropos," meaning "turning or changing direction." Lyotropic liquid crystals are formed from amphiphilic molecules, which have both hydrophilic (water-loving) and hydrophobic (water-fearing) parts. The orientation and organization of these molecules depend on the concentration of solvent in the system. The lyotropic mesophases include cubic, hexagonal, and lamellar phases, which are based on the geometry and arrangement of the organized structures.

Lamellar Phase :

The lamellar phase is composed of amphiphilic bilayers located between the oil and water phases. The bilayer structure helps to minimize contact between the oil and aqueous phases, making it useful for drug encapsulation. As the concentration of water or medication increases, the thickness of the bilayer increases depending on how it partitions in a specific oil or water phase[13,14].

Hexagonal Phase :

Surfactant micelles can form higher-order 2-D structures in the hexagonal phase, including a higher hierarchy of cylindrical micelles. The hexagonal phase can either be a regular hexagonal phase or a reverse hexagonal phase, depending on the aqueous environment. In the normal hexagonal phase, the polar head is exposed to the aqueous medium, while the hydrophobic acid chain faces inward. In contrast, the reverse structure occurs under anhydrous or low aqueous conditions, where the hydrophilic tail forms the inner core, and the hydrocarbon chains are oriented towards the non-aqueous media, creating a reversed hexagonal phase. Hexagonal liquid crystals have a fan-like texture when viewed under polarising light microscopy. These structures can be useful for drug delivery systems[15,16].

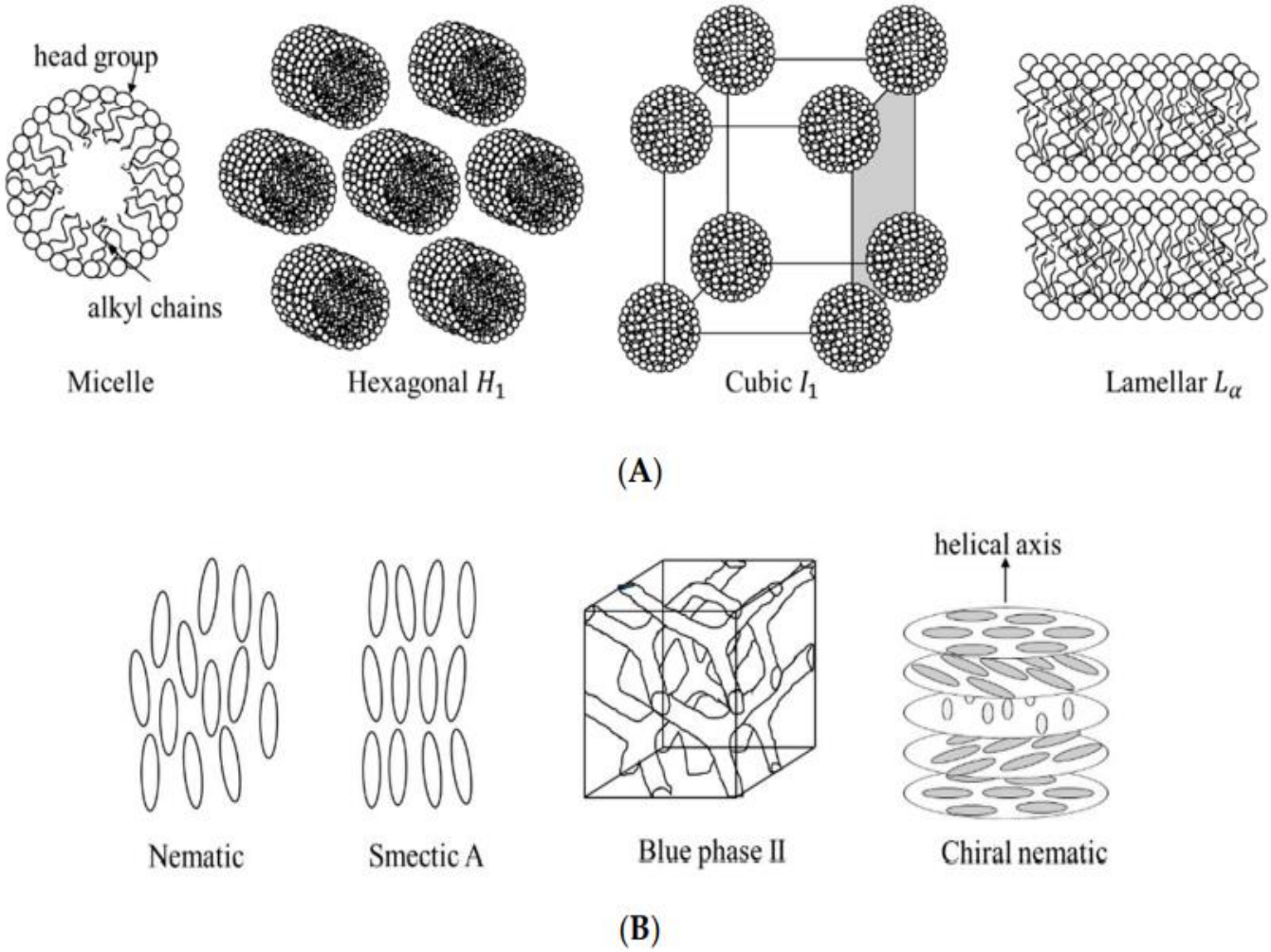
Cubic Phase :

The cubic liquid crystal is composed of a continuous bilayer of lipid with a thickness of approximately 3.5 nm and non-contacting aqueous channels that increase the interfacial area of the cubic channel to approximately 400 m2/g. This phase is subdivided into three classes, namely the body-centered cubic lattice phase, the gyroid lattice cubic lattice phase, and the double diamond lattice cubic phase. They are stiffer than other mesophases, allowing for controlled drug release, with a higher capacity for medication loading. They are also more resistant to dilution than other LC phases. However, extremely water-soluble medications cannot be incorporated because of the high amount of water present[17,18].

Gel Phase :

The gel phases share similarities in structure with the lamellar phases, but they exhibit high viscosity due to the highly regular intermolecular arrangements found in phospholipid bilayers. These phases are characterized by amphiphiles with one or two alkyl chains in an all-trans conformation that form rigid layers. Four distinct lyotropic gel phases have been identified: subgel (Lc), lamellar gel phases (Lb or Lb'), rippled phases (Pb'), and liquid crystalline or fluid phase (La)[19,20]

Fig.1 Structural design of Lyotropic (A) and Thermotropic (B) liquid crystal phases[21].



COMPOSITION , PREPARATION AND CHARACTERIZATION OF LIQUID CRYSTALS :

COMPOSITION OF LIQUID CRYSTAL NANOPARTICLE :

I. AMPHIPHILIC MOLECULES

Self-assemble in an aqueous environment to reduce unfavorable interactions between their hydrophobic component and water.

The formation of the lyotropic phases depends on three factors:

1] the amphiphilic molecules,
2]the appropriate solvent (water for biological applications)
3] the temperature.

The parameters of the mesophases can be altered by external variables like as pressure, pH, and salt concentrations in addition to temperature[22]. Just a small number of amphiphilic compounds have been employed as LLC NPs in drug administration, despite the fact that many of them have been reported as displaying lyotropic liquid-crystalline behaviour in water. The main limiting

factor is its stability in physiological media. These amphiphilic compounds include GMO and similar molecules (such monolinolein), as well as combinations of GMO and other lipids.

The first chemicals to be studied for the formation of structured nanoparticles included these substances [23]. The GMO analogues are less stable against enzymes due to an ester bond and one or more unsaturations in the aliphatic chain. The reverse cubic lattice is forced to become a reverse hexagonal one by the partial breakdown of GMO at physiological temperature. Investigating phytantriol was done to find a solution to this problem. When temperatures are physiological, it also produces cubic mesophases [24,25].

In order to improve its resistance to being broken down by enzymes, phytantriol's aliphatic chain is methyl branched and completely saturated [26]. By adding tiny chemicals, such as tetradecane or vitamin E, the temperature at which the inverse hexagonal mesophase (H2) is formed may be lowered to physiological levels, allowing for a more regulated occurrence of the phase [27,28].

An alternative remedy is to add a glycerate group to the traditional GMO head. When circumstances are physiological, (H2) mesophases can emerge thanks to these minute alterations[29].

II. STABILIZERS

To prevent aggregation over time, nanoparticle dispersions must be stabilized. The type and concentration of stabilizers are not meaningless because they can influence crucial factors such the creation of mesophases, toxicity, and protection against hydrolysis. To prevent the flocculation of nanoparticles, pluronic copolymers are a viable option[30].
These are triblock copolymers, EOx—POy—EOx, with two outward portions made of ethylene oxide units (EO) and one core component made of propylene oxide units (PO).

a) The PO block is in charge of the polymer's adherence to the nanoparticle,
b) EO blocks function as steric agents and prevent flocculation.

The hydrophilic/lipophilic balance is a crucial characteristic and both components are necessary. The triblock copolymer EO99—PO67—EO99, often known as Pluronic F127 or Poloxamer 407, is the most used pluronic stabilizer.A lower concentration of Pluronic F127 creates larger nanoparticles, whereas a greater concentration of Pluronic F127 promotes smaller ones. Pluronic F127 is also known as Poloxamer 407[31].
GMO-based nanoparticles of 1.0% weight and phytantriol-based ones at 0.5% weight may both be evenly dispersed using pluronic F127. Nevertheless, it is not the best Pluronic to stable these nanoparticles, and F108, EO132—PO50—EO132 a higher capacity to stabilize cubosomes with less change of the interior mesophase structure[32]. Since it extends the H2 mesophase domain for phytantriol and GMO, b-casein was also utilized as a stabilizer [33].
Specific LLC Nanoparticle stabilizers, disk-like Laponite clay particles for GMO/tetradecane/water systems, and spherical silica colloids for phytantriol/tetradecane/water systems are a few more non-organic structures that have been reported.

PREPARATION OF LIQUID CRYSTAL NANOPARTICLES :

Drugs that are hydrophilic and lipophilic have been placed into LLC NPs. Before being dispersed, the medication is typically dissolved in the bulk mesophase. Hydrophobic regions of the nanostructures house lipophilic chemicals. These medications can occasionally be found close to hydrophilic regions, which causes changes to the curvature towards the water channels[34]. After dispersion, hydrophilic medicines stay in the water channels[29].

Drug loaded Lyotropic Liquid Crystal Nanoparticles are typically prepared for use in drug delivery using two methods :

A top-down approach

The stabilizers and amphiphile mixture are first hydrated, enabling them to self-assemble into a viscous mass. The mass is then evenly distributed in an aqueous solution while being highly energetic. Ultrasonication and high-pressure homogenization are frequently used processes. It must be noted that all of these approaches involve heating the materials, which can severely harm amphiphilic molecules or medications in capsule form. The bulk mesophase, which includes the medication and the stabilizers, has been dispersed using a shear device based on a Couette cell to prevent this damage[35]. The benefits of this technique include reducing the amount of heating energy used and creating monodisperse LLC NPs with high concentrations of lipophilic compounds quickly (up to 70% wt).

A bottom-up approach.

In this method, hydrotropes and amphiphiles are combined before dilution. Hydrotropes, which are utilized to increase nanoparticle solubility but may also cause toxicity, are a significant problem. A controlled addition of an aqueous medium causes a fast reduction in the lipid solubility in the amphiphile/hydrotrope solution, which leads to the generation of distributed LLC NPs. This method's benefit of producing nanoparticles with greater stability is that it is more widely available [36].

Both methods generate vesicles that may interfere with the drug release mechanism in addition to Lyotropic Liquid Crystal Nanoparticles, which are thought to be produced in both cases.

There are three methods for cleaning Lyotropic Liquid Crystal Nanoparticles solutions :

METHOD 1	METHOD 2	METHOD 3
The Heat Therapy (usually above 120 C). By creating organized cubic particles from smaller vesicles, it is utilized to purify cubosomes. The solubility of the surfactant actually reduces as the temperature rises, and vesicles fuse to form new nanoparticles. It has been shown that GMO-based cubosomes with narrow particle size and well-defined interior structure may be manufactured in a scalable and repeatable manner using a combination of shear energy homogenization and heat treatment [37].	**Modified Dialysis Approach**, which Abraham et al. first developed in 2004 and which stays away from high-energy procedures. It combines dialysis with the bottom-up strategy.	**Premix Membrane Emulsification**, and it is a process in which a predispersed emulsion is repeatedly extruded through a membrane with desired-sized holes to create smaller emulsion droplets. A monodisperse nanoparticle solution may be created using this method [40].
A rise in temperature is necessary, the use of this purification process is essentially limited to particular circumstances and isn't always appropriate for drug delivery applications [38].	To create a solution devoid of hydrotropes and micelles, the bulk phase of lipid is combined with water, hydrotropes, and Pluronic before being dialyzed against water[39].	The creation and stability of cubosomes or hexosomes have recently been shown to be generated or modulated by altering various solution properties including pH or ionic strength. Without the use of significant energy, these methods enable the production of the desired nanostructure. Phosphate buffer was added to an aqueous solution of cationic vesicles to achieve cubosome dispersion[41].

Characterization of Liquid Crystal Nanostructures :

SR NO	INSTRUMENT	IMPORTANT FEATURE	REFERENCE
1.	**Small-angle X-ray Scattering (SAXS)**	The most effective method for studying mesophases. Bragg peaks are defined as the regions where the incoming X-rays scatter the most due to the nanoparticles' periodic structure. Databases and derived Bragg peaks may be compared to identify recurring assemblies (double diamond, gyroid, primitive cubic, discontinuous cubic or hexagonal). Synchrotron X-ray sources must be utilised in order to produce diffractograms of greater quality and shorten acquisition times. It has been able to analyse events using this method, such as the transition from lamellar to cubic mesophases or the transition from cubic to hexagonal mesophases when vitamin E is added.	42
2.	**Differential Scanning Calorimetry (DSC)**	DSC can provide additional types of information, such as details on how an encapsulated medicine interacts with the mesophase. Phase changes can be researched.	43,44

3.	**Cryogenic Transmission Electron Microscopy (cryoTEM)**	The nanoparticles' size and shape to be determined. To prevent changing nanoparticle architectures, the sample must be vitrified. Just a small number of particles may be visible due to the slow acquisition time. Moreover, rapid Fourier transform analysis combined with cryo-TEM can be employed to identify the mesophase.	45,46
4.	**Cryo Field Emission Scanning Electron Microscopy (cryo-FESEM)**	Is an additional method for examining the nanoparticles' structure. It enables the same kind of particle in solution observation as cryo-TEM. Although Cryo-FESEM cannot be utilised to identify the kind of mesophase. it does offer more surface-level information on the materials than Cryo-TEM. To further understand the morphology of the LLC NPs, atomic force microscopy is also employed.	47,48
5.	**Dynamic Light Scattering (DLS)**	Provides details on the size across a greater number of nanoparticles. The LLC NP dispersion's colloidal stability may be regulated by periodically taking size measurements. Centrifugation is a technique that can shorten experiment duration. The process of centrifugation quickens the dispersed particle's movement; 300 rpm is equivalent to multiplying the gravimetric factor by 12. In analysing light transmission, there are devices that allow the sample to be centrifuged, providing information on regional nanoparticle concentration and demixing processes.	49,50
6.	**13C Nuclear Magnetic Resonance (13CNMR)**	In general, diffusion into and out of the water channels of the nanoparticles is investigated. Local intermolecular interactions can change a particular 13C's chemical shift. Information on the diffusion speed of tiny and big molecules in solution is available from relaxation experiments. For instance, studies have been done on the migration of Eu3+ or 23Na from the exterior medium to the inside of cubosomes. These studies also provide details regarding the internal structure of the nanoparticle, the existence of cubic or hexagonal mesophases, and the stability over time (particularly resistance to hydrolysis).	51,52
7.	**Infrared (IR) Spectroscopy**	Is a good method for examining molecular interactions. The interactions between the nanoparticles, the surfactant, the external medium, and the loaded medication are shown by attenuated total reflectance. The method's ease of use makes it possible to analyze the stability of interactions while taking into account changes in a variety of variables, including temperature, pH, stabilizer concentration, and the adsorption of nanoparticles on surfaces.	53,54

Newly published drug delivery systems based on Lyotropic Liquid Crystal agents targeted at various disorders and administered through various vial types Nanoparticles employ various therapeutic effects :

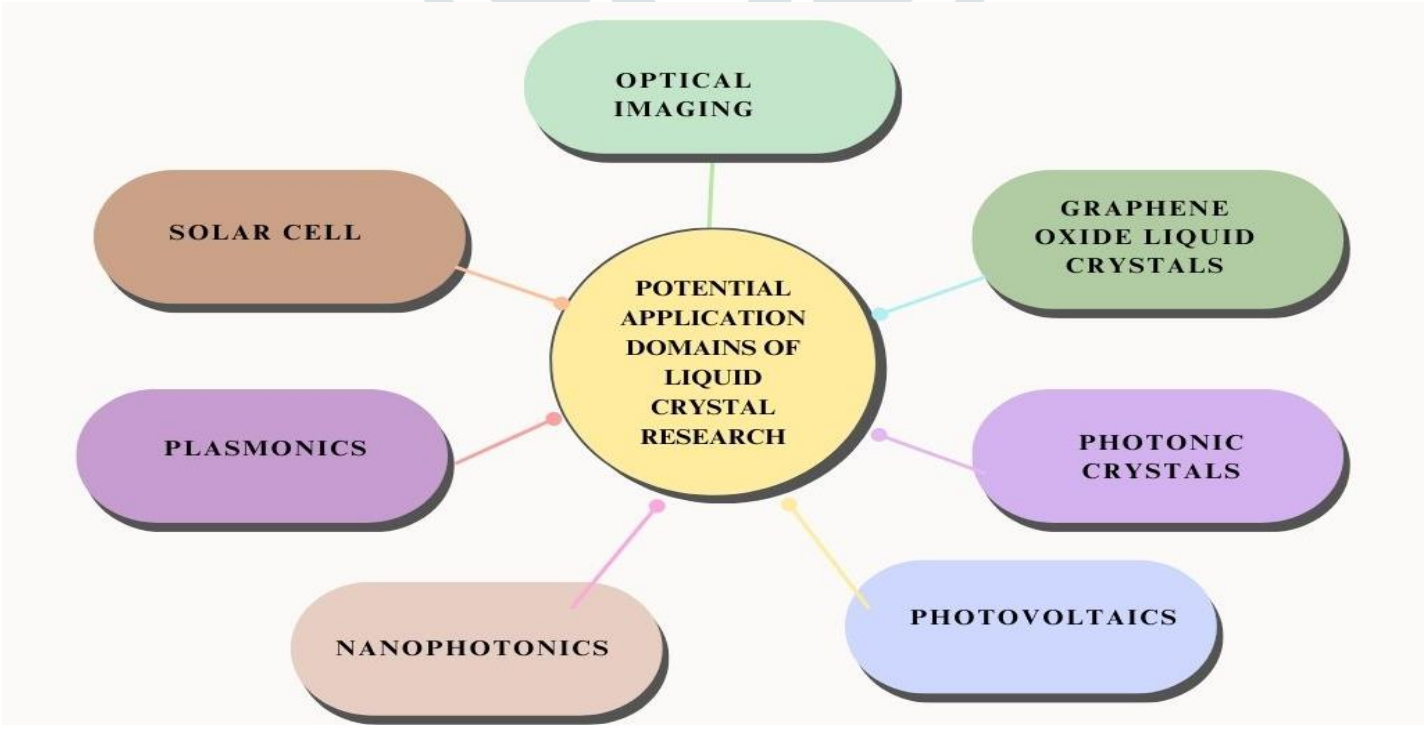
LC NANOPARTICAL	DRUG	AMPHIPHILE STABILIZERS	DISEASES	ROUT OF ADMINIST -RATION	SPECIAL FEATURES	REF
Hexosomes	Irinotecan	Oleyl glycerate or phytanyl glycerate Pluronic F127	Cancer (metastasis of colorectal cancer)	Intravenous	Even at neutral pH, irinotecan remains in its active lactone form within hexosomes.	55
Cubosomes + hexosomes	Paclitaxel	SPC/GDO polysorbate 80 (P80)/ ethanol	Cancer	Oral	Oral bioavailability is 2.1 times greater than that of commercial Taxol.	56
Cubosomes	Quercetin + fluorescent probes	GMO Pluronic F108	Cancer theranostic applications	Oral	In vitro experiments	57
Cubosomes	Cinnarizine	Phytantriol Pluronic F127	See thickness	Oral	Phytantriol cubosomes increase the oral bioavailability of the compound.	58
Cubosomes	Ibuprofen	Phytantriol Pluronic F127	Anti-inflammatory drug	Oral	Increased medication absorption	59
Cubosomes	Dexamethasone	GMO Pluronic F127/glycerol	Posterior segment eyes diseases	Ophthalmic	Trans-corneal permeability has improved.	60
Cubosomes	Flurbiprofen	Cataract surgery	Cataract surgery	Ophthalmic	Preparation of flurbiprofen without irritation	61
Cubosomes	S14G-HN adjuvant: Odorranalectin	GMO/MAL-PEG--OA Pluronic F127	Central nervous system disorders, Alzheimer's disease	Intranasal	Odorranalectin's impact on certain targets increased mucoadhesive capacity for effective transport to the brain	62
Hexosomes	siRNA	GMO/OA/OAM GMO/OA/PEI Pluronic F127	Gene-caused diseases	Topical	More skin penetration without irritation	63
Cubosomes	FITC--ovalbumin	Phytantriol Pluronic F127/ PEG200 or propylene glycol	Vaccine	Intravenous	Discharge that continues after the first explosion. Release from PHY cubosomes occurs more slowly than from GMO cubosomes (In vitro	64

					studies)	
Cubosomes	FITC--ovalbumin adjuvants: imiquimod or MPL	Phytantriol Pluronic F127/ PEG200 or propylene glycol	Vaccine	Intravenous	Immune cells react to liposomes carrying ova and adjuvants more strongly.	65
Cubosomes	Ovalbumin adjuvant: Quil A	Phytantriol Pluronic F127/ PEG200 or propylene glycol	Vaccine	Intravenous	For slow subunit-antigen release, chitosan, a thermosensitive hydrogel, is embedded with cubosomes.	66

APPLICATIONS :

Since its discovery in 1888, liquid crystals have been regarded as an odd material. Research into liquid crystal electro-optical features was sparked by the requirement for low-power, high-efficiency displays, and they have a variety of applications outside of displays, such as switchable windows, thermometers, plasmonics, photovoltaics, and solar cells [67].

Fig.2 Applications of Liquid Crystals in various aspects of daily life



FUTURE PROSPECTIVE :

In recent years, it has become apparent that liquid crystalline lasing technology is developing quickly. full-color lasing combinations created from RGB subpixels.

(a) The lasing spectra of various RGB subpixel arrangements. Matching PL pictures and CIE1931 coordinates determined from appropriate spectra are shown as insets. Scale bars: 20 m.
(b) The CIE1931 colour diagram's lasing peak chromaticity distribution. Seven spectra were used to isolate the peaks in (a).
(c) A far-field image of a "LCLD" pattern made up of several RGB pixel arrays. A mobile phone's built-in digital camera was used to take the picture. The scale bar length is 150 m [68].

The variety of LC mesophases (such as cholesteric, nematic, or blue phases [69,70] and the numerous intriguing concepts for using them in the context of light amplification were reported in the last decade and will be presented in the coming years. Because of these elements, this study field is exceptional and rapidly developing. The concept of band-edge lasing [71], devoted to the production of the ultimate light source in the future, was implemented using the many LC mesophases and their distinctive features [72].

Fascinatingly, researchers have suggested that the industry has implemented principles that underlie the creation of LC-dye hybrid systems. The utilization of contemporary and recently created chromophores, such as BODIPY-dyes, that have useful features for band-edge lasing is made possible by this method in a variety of ways. It is crucial to emphasise that this group of dyes is created, functionalized, and investigated in order to utilize them in lasing technologies due to their exceptional thermal- and photostability [73].

For instance, creating reliable, effective OLED- and WOLED-based devices is one of the primary objectives for contemporary optoelectronic technology (dedicated to progressive and improved TV screens, monitors, projectors, displays, and novel lighting technologies, such as Li-Fi). New hybrid materials, like LCs, are avidly tested for this purpose. They enable the development of many systems, which can take the shape of thin layers, LC cells, or microscopic droplets. Moreover, they may be modularly incorporated into several different organic and inorganic materials, including functional devices and polymers, and elastomers[74,75].

Studying the novel active hybrid systems enables lasing property optimization and aids in integrating them with previously well-known devices to create applications, such as biological labels, fluorescent switches, and sensors [76.]

LCs are excellent for usage in medical and biological applications because of their adaptability to structural, thermal, and optical tuning and their capacity to assemble into 3D structures. They can combine with QDs to build systems that provide the benefits of both types of materials, including flexibility, sensitivity, and high photostability.

Wide-broadband lasing devices with self-healing capabilities and quick responses to environmental changes can be made possible by the use of these materials thanks to the electrical control of LC mesophases. The uncommon LC structures, such as Blue Phases, which are renowned for their enhanced temporal responsiveness of LCD, are worth mentioning one again. Insight into the specific kinds of LCs that may discriminate tunability and outstanding lasing emission qualities [77] will be crucial in the future. These LCs may be made feasible by new, ultra-fast light modulators, high-resolution displays, or tunable photonic crystals [78].

DFB lasers are intriguing devices for the inclusion of fresh approaches and potential advancements due to their great sensing capabilities, comparatively high light output power, and ease of production. Very likely because to this, new concepts continue to be used in studies and for commercial purposes, such as in contemporary DFB-LC hybrid systems. The process is based on photopolymerization or nanoimprinting UV technology, and it creates dependable sensors that can be made smaller and more adjustable[79]. In the context of creating surface-emission junction lasers, sensing capabilities, the potential for precise layer thickness control, as well as the capacity to emit three primary colours concurrently, are especially noteworthy (e.g., PSCLC and VCSEL).). Among the potential applications for these constructs are laser printers, lidars, and 3D sensors. Several researchers from diverse fields have looked at the random lasing phenomena. It has been demonstrated that this type of technology paves the way for the creation of contemporary gadgets devoted to laser-based displaying, identification systems, biosensing, and lighting applications (Li-Fi idea).

Nematic LC mesophase-achieved RL is characterized by simple tunability brought on by heat flow[80], electric, or magnetic fields. The RL emission that is produced is effective and simple to tune; in the case of LCs, this tuning is additionally made feasible by externally applied fields (magnetic/electric), mechanical stress, or temperature. Additionally, the ultra-low RL threshold may be attained by utilizing various LC materials, such as cholesteric mesophase. Lighting, imaging, fluorescence microscopy, the development of cutting-edge laser displays, biological sensing, chemical monitoring, identification, and communication are some of the opportunities for RL [81]. By using LC in conjunction with QDs, a different lasing process that has been mentioned can be accomplished. In this instance, it is possible to see the SPR phenomenon, which contributes to a large drop in the lasing threshold [82].

It is noteworthy that the Perovskite materials utilized for lasers have extremely appealing 3D and other nanostructures (e.g., nanoplates, nanoparticles). It is important to note that in this situation, it is possible to produce extremely effective light amplification along with a narrowing of the acquired spectrum that points to the one-mode RL phenomena [83,84].

Future and the last ten years 2339 PDLC microlasers make up the following category of LC lasers and are a great topic for discussion. Future applications in optoelectronic devices, as well as for biology and medicine, should be distinguished. The

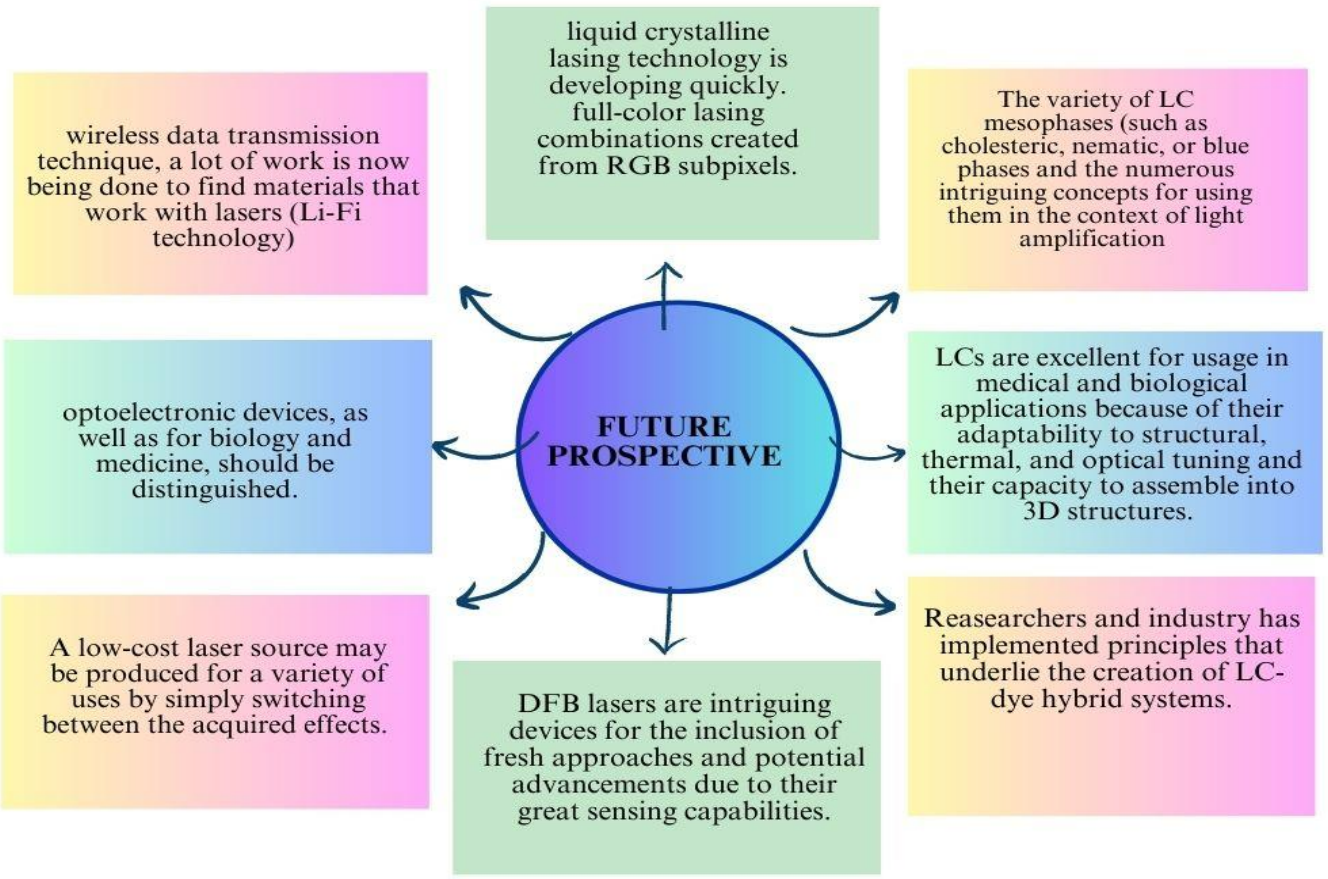
innovative independent tiny lasers, for instance, may be inserted into the cornea, skin, and entire blood, paving the way for long-term diagnostics and sensor data collection. When LCs are utilized deliberately, droplets with certain sizes of resonators may form.

Nowadays, it is feasible to design a gadget with a powerful beam and a tiny footprint (range of micrometers). Furthermore, at the fabrication stage, it is simple to adjust the size, quantity, and dispersion of droplets. Also, a number of simple procedures (homogenization in an ultrasonic water bath or the utilisation of a vortex) can be further researched. The disorganised nature of PDLCs may provide the groundwork for achieving a low lasing threshold. Even in the same system, a change in droplet size may make it possible to produce band-edge lasing [85].

A low-cost laser source may be produced for a variety of uses by simply switching between the acquired effects. Recalling the WGM process, which is distinguished by a high Q factor, is important when discussing lasing from a droplet cavity. These lasers' design and compact size are primarily intended for soft-matter-based bio- or chemosensors and miniature lasers [86].

In order to improve a truly wireless data transmission technique, a lot of work is now being done to find materials that work with lasers (Li-Fi technology). Many white light sources are required for this purpose. As a result, LC mesophase-formed microresonators make excellent candidates for systems that emit two and three hues, as well as white light. LC-based lasers have a wide range of uses, including cutting-edge data delivery and illumination technologies (like Li-Fi), sensing and biosensing, and display technologies. It is difficult to predict how much the lasers will need to be modified for future use—whether that means they will need to be made smaller, more flexible, or even more complex.As LCDs, LCs were once widely used, as is known, however LED and OLED have now supplanted this technology as being considerably more useful. The features of LCs, however, should be kept in mind as they are still quite important and are yet not fully understood.

Fig.3 Future Prospective of Liquid Crystal



CHALLENGES AND PROBLEMS :

Liquid crystals have been a major topic since the previous decade, and a lot of work has been done in understanding their challenging process and alignments in a variety of applications, primarily in display displays. Yet, the largest problem now facing

the liquid crystals business is that quite a few crucial alignment issues, particularly those related to liquid crystals molecular interactions, are not fully understood. The proposed alignment technique is required to overcome the current constraints impacting display quality and processing costs. Liquid crystals' unique difficulties include multi-domain alignment pattern combinations, picture sticking, uneven display brightness, and non-uniform alignment over huge screens [87].

Another issue that is crucial in display applications is the response time of liquid crystals. Because to the non-adjustable pre-tilt angle of liquid crystals with the substrate, which ultimately has an impact on cell dynamics, slow reaction time of liquid crystals produces blur quality and unfavourable picture presentation. A appropriate orientated angle adjustment between liquid crystals and substrate must be addressed in order to increase picture quality and presentation [88].

Moreover, the anchoring energy may be utilized to measure the liquid crystal's alignment strength. This energy is required to deviate the director off the molecular axis at a given angle. To obtain uniform planer alignment, stability of the anchoring energy, which is related to the pre-tilt angle, is another major challenge for the liquid crystal industry. To solve this issue, the rubbing mechanism was introduced. However, this mechanism also has problems, such as static charge accumulation and dust-particle generation on the crystal surface, which affect the fundamental device characteristics and operational mechanism. An important factor in assessing the quality of a liquid crystal display is the phenomenon known as "picture sticking," which occurs when an image is shown for an extended period of time. The current state of the liquid crystal issue is, in reality, the electric charge or residual DC charge created on the liquid crystal surface during long-term image display, which results in the selective surface adsorption of ionic impurities contained in the liquid crystal material or layers [87].

Additionally, liquid crystals have some other drawbacks related to the enormous amount of ionic impurities found in their aligned layers and the presence of conjugated functional groups or lone pairs in their molecules as well as between their aligned layers, which would ultimately disturb and disrupt the display application and thus affect the use of liquid crystals in device applications [89].

CONCLUSION :

Drug-loaded liquid crystals have emerged as a promising drug delivery system due to their unique structural characteristics and advantages over traditional drug delivery methods. The ability to control drug release, improve bioavailability, and target delivery to specific sites makes liquid crystal-based drug delivery an attractive option for drug formulation. Different types of liquid crystal phases, such as lamellar, cubic, and hexagonal phases, have been investigated for drug delivery applications. The lamellar phase, which is a continuous bilayer structure, has been extensively studied for its potential as a drug delivery vehicle due to its high interfacial area and the ability to control drug release. Cubic phases, on the other hand, are characterized by the presence of interpenetrating channels, and their high viscosity makes them suitable for sustained drug release. The hexagonal phase, which has a two-dimensional periodic structure, has been explored for its potential in transdermal drug delivery. Several studies have been conducted to investigate the behavior of drugs in liquid crystal phases, and successful drug-loaded liquid crystal formulations have been reported for various drugs such as ibuprofen, diclofenac, and paclitaxel. However, there is still much room for future research in this field. One potential avenue for research is the investigation of new types of liquid crystal phases that could further improve drug delivery efficiency. Optimization of drug loading and release from liquid crystal formulations is another area that requires further investigation to achieve optimal therapeutic efficacy. Moreover, exploring the potential of liquid crystal-based drug delivery for different routes of administration, such as oral, injectable, and ocular routes, could expand the application of liquid crystals in drug delivery. In summary, drug-loaded liquid crystals are a promising drug delivery system with several advantages over traditional drug delivery methods. The unique structure of liquid crystals allows for controlled drug release, improved bioavailability, and targeted delivery. Research in this field has yielded promising results, and future investigations could further enhance the potential of liquid crystal-based drug delivery for clinical applications.

REFERENCES :

[1] Stephen, M. J.; Straley, J. P. Physics of Liquid Crystals. Rev. Mod. Phys. 1974, 46, 617–704.

[2] Hird M. Fluorinated liquid crystals--properties and applications. Chem Soc Rev. 2007 Dec;36(12):2070-95. Epub 2007 Sep 14.

[3] Shlens, M.; Stoltz, M. R.; Benjamin, A. Orthopedic Applications of Liquid Crystal Thermography. West. J. Med. 1975, 122, 367–370.

[4] Andrienko, D. "Introduction to liquid crystals", International Max Planck Research School. 2006. https://www.researchgate. net/publication/253894173_Introduction_to_liquid_crystals/ (accessed Jun 6, 2017).

[5] Mona Sargazi, Matthew R. Linford & Massoud Kaykhaii (2018): Liquid Crystals in Analytical Chemistry: A Review, Critical Reviews in Analytical Chemistry,

[6] Carrión FJ, Martínez-Nicolás G, Iglesias P, Sanes J, Bermúdez MD. Liquid crystals in tribology. Int J Mol Sci. 2009 Sep 18;10(9):4102-4115.

[7] Stephen, M. J., & Straley, J. P. (1974). Physics of liquid crystals. Reviews of Modern Physics, 46(4), 617–704.

[8] W.H. de Jeu, Introduction to thermotropic liquid crystal phases, in: S. Martellucci, A.N. Chester (Eds.), Phase Transitions in Liquid Crystals. NATO ASI Series (Series B: Physics) 290, Springer, Boston, MA., 1992.

[9] P. Ukleja, Liquid Crystals (Physics), in: R.A.B.T.-E. of P.S. and T. Third E. Meyers (Ed.), Academic Press, New York, 2003, pp. 717–739.

[10] H.K. Bisoyi, S. Kumar, Discotic nematic liquid crystals: science and technology, Chem. Soc. Rev. 39 (2010) 264–285.
[11] A. Taugerbeck, C.J. Booth, Design and synthesis of chiral nematic liquid crystals, Handb. Liq. Cryst. (2014) 1–63.
[12] E. Sackmann, S. Meiboom, L.C. Snyder, Relation of nematic to cholesteric mesophases, J. Am. Chem. Soc. 89 (1967) 5981–5982.
[13] Y.-Y. Chen, H.-C. Wu, J.-S. Sun, G.-C. Dong, T.-W. Wang, Injectable and thermoresponsive self-assembled nanocomposite hydrogel for long-term anticancer drug delivery, Langmuir. 29 (2013) 3721–3729.
[14] M.A.-M. Mir Maria Ahmed, Naveed Rehman, Asim Ur, Recent applications of PLGA based nanostructures in drug delivery B Biointerfaces, Colloids Surf. A Physicochem. Eng. Asp. 159 (2017) 15–231.
[15] Y. Chen, P. Ma, S. Gui, Cubic and hexagonal liquid crystals as drug delivery systems, Biomed. Res. Int. 2014 (2014), 815981.
[16] Q.-Q. Shan, X.-J. Jiang, F.-Y. Wang, Z.-X. Shu, S.-Y. Gui, Cubic and hexagonal liquid crystals as drug carriers for the transdermal delivery of triptolide, Drug Deliv. 26 (2019) 490–498.
[17] C.R. Thorn, C.A. Prestidge, B.J. Boyd, N. Thomas, Pseudomonas infection responsive liquid crystals for glycoside hydrolase and antibiotic combination, V.P. Chavda et al. Journal of Controlled Release 349 (2022) 533–549 546 ACS Appl. Bio Mater. 1 (2018) 281–288.
[18] C. Brasnett, G. Longstaff, L. Compton, A. Seddon, Effects of cations on the behavior of lipid cubic phases, Sci. Rep. 7 (2017) 8229.
[19] Lancelot, A., Sierra, T., & Serrano, J. L. (2014). Nanostructured liquid-crystalline particles for drug delivery. Expert Opinion on Drug Delivery, 11(4), 547–564.
[20] S. Hyde, B.W. Ninham, S. Andersson, K. Larsson, T. Landh, Z. Blum, S. Lidin, Chapter 5 - Lipid self-assembly and function in biological systems, in: S. Hyde, B. W. Ninham, S. Andersson, K. Larsson, T. Landh, Z. Blum, S.B.T.-T.L. of S. Lidin (Eds.), Elsevier Science B.V., Amsterdam, 1997, pp. 199–235.
[21] Nagaraj M. Liquid Crystals Templating. *Crystals*. 2020; 10(8):648.

[22] Fong C, Le T, Drummond CJ. Lyotropic liquid crystal engineering ordered nanostructured small molecule amphiphile self-assembly materials by design. Chem Soc Rev 2012;41(3):1297-322.
[23] Shah JC, Sadhale Y, Chilukuri DM. Cubic phase gels as drug delivery systems. Adv Drug Deliver Rev 2001;47(2-3):229-50.
[24] Barauskas J, Landh T. Phase behavior of the phytantriol/water system. Langmuir 2003;19(23):9562-5.
[25] Dong YD, Dong AW, Larson I, et al. Impurities in commercial phytantriol significantly alter its lyotropic liquidcrystalline phase behavior. Langmuir 2008;24(13):6998-7003.
[26] Tilley A, Dong YD, Amenitsch H, et al. Transfer of lipid and phase reorganisation in self-assembled liquid crystal nanostructured particles based on phytantriol. Phys Chem Chem Phys 2011;13(8):3026-32.
[27] Dong YD, Larson I, Hanley T, et al. Bulk and dispersed aqueous phase behavior of phytantriol: effect of vitamin E acetate and F127 polymer on liquid crystal nanostructure. Langmuir 2006;22(23):9512-18.
[28] Yaghmur A, de Campo L, Sagalowicz L, et al. Emulsified microemulsions and oil-containing liquid crystalline phases. Langmuir 2004;21(2):569-77.
[29] Boyd BJ, Whittaker DV, Khoo SM, et al. Lyotropic liquid crystalline phases formed from glycerate surfactants as sustained release drug delivery systems. Int J Pharm 2006;309(1-2):218-26.
[30] Gustafsson J, Ljusberg-Wahren H, Almgren M, et al. Submicron particles of reversed lipid phases in water stabilized by a nonionic amphiphilic polymer. Langmuir 1997;13(26):6964-71.
[31] Amar-Yuli I, Wachtel E, Shoshan EB, et al. Hexosome and hexagonal phases are mediated by hydration and polymeric stabilizer. Langmuir 2007;23(7):3637-45.
[32] Chong JYT, Mulet X, Waddington LJ, et al. Steric stabilization of self-assembled cubic lyotropic liquid crystalline nanoparticles: high throughput evaluation of triblock polyethylene oxidepolypropylene oxide-polyethylene oxide copolymers. Soft Matter 2011;7(10):4768.
[33] Zhai J, Waddington L, Wooster TJ, et al. Revisiting beta-casein as a stabilizer for lipid liquid crystalline nanostructured particles. Langmuir 2011;27(24):14757-66.
[34] Efrat R, Kesselman E, Aserin A, et al. Solubilization of hydrophobic guest molecules in the monoolein discontinuous Ql cubic mesophase and its soft nanoparticles. Langmuir 2008;25(3):1316-26.

[35] Salentinig S, Yaghmur A, Guillot S, et al. Preparation of highly concentrated nanostructured dispersions of controlled size. J Colloid Interface Sci 2008;326(1):211-20.
[36] Spicer PT, Hayden KL, Lynch ML, et al. Novel process for producing cubic liquid crystalline nanoparticles (cubosomes). Langmuir 2001;17(19):5748-56.
[37] Barauskas J, Johnsson M, Joabsson F, et al. Cubic phase nanoparticles (cubosome†): principles for controlling size, structure, and stability. Langmuir 2005;21(6):2569-77.
[38] W€orle G, Siekmann B, Koch MHJ, et al. Transformation of vesicular into cubic nanoparticles by autoclaving of aqueous monoolein/poloxamer dispersions. Eur J Pharm Sci 2006;27(1):44-53.
[39] Abraham T, Hato M, Hirai M. Glycolipid based cubic nanoparticles: preparation and structural aspects. Colloids Surf B Biointerfaces 2004;35(2):107-18.
[40] Joseph S, Bunjes H. Preparation of nanoemulsions and solid lipid nanoparticles by premix membrane emulsification. J Pharm Sci 2012;101(7):2479-89.
[41] Muir BW, Zhen G, Gunatillake P, et al. Salt induced lamellar to bicontinuous cubic phase transitions in cationic nanoparticles. J Phys Chem B 2012;116(11):3551-6.
[42] Angelov B, Angelova A, Vainio U, et al. Long-living intermediates during a lamellar to a diamond-cubic lipid phase transition: a small-angle x-ray scattering investigation. Langmuir 2009;25(6):3734-42.

[43] Gong X, Moghaddam MJ, Sagnella SM, et al. Lyotropic liquid crystalline self-assembly material behavior and nanoparticulate dispersions of a phytanyl pro-drug analogue of capecitabine-A chemotherapy agent. ACS Appl Mater Interfaces 2011;3(5):1552-61.

[44] Cohen-Avrahami M, Libster D, Aserin A, et al. Sodium diclofenac and cell-penetrating peptides embedded in H (II) mesophases: physical characterization and delivery. J Phys Chem B 2011;115(34):10189-97.

[45] Kuntsche J, Horst JC, Bunjes H. Cryogenic transmission electron microscopy (cryo-TEM) for studying the morphology of colloidal drug delivery systems. Int J Pharm 2011;417(1-2):120-37

[46] Sagalowicz L, Michel M, Adrian M, et al. Crystallography of dispersed liquid crystalline phases studied by cryotransmission electron microscopy. J Microsc 2006;221(2):110-21.

[47] Rizwan SB, Dong YD, Boyd BJ, et al. Characterisation of bicontinuous cubic liquid crystalline systems of phytantriol and water using cryo field emission scanning electron microscopy (cryo FESEM). Micron 2007;38(5):478-85.

[48] Neto C, Berti D, Aloisi GD, et al. In situ study of soft matter with atomic force microscopy and light scattering. In: Buckin V, editor. Trends in colloid and interface science XIV. Berlin Heidelberg: Springer; 2000. p. 295-9.

[49] Salonen A, Moitzi C, Salentinig S, et al. Material transfer in cubosome-emulsion mixtures: effect of alkane chain length. Langmuir 2010;26(13):10670-6.

[50] Libster D, Aserin A, Yariv D, et al. Soft matter dispersions with ordered inner structures, stabilized by ethoxylated phytosterols. Colloids Surf B Biointerfaces 2009;74(1):202-15.

[51] Nakano M, Sugita A, Matsuoka H, et al. Small-angle x-ray scattering and 13C NMR investigation on the internal structure of "cubosomes". Langmuir 2001;17(13):3917-22.

[52] Monduzzi M, Ljusberg-Wahren H, Larsson K. A 13C NMR study of aqueous dispersions of reversed lipid phases. Langmuir 2000;16(19):7355-8.

[53] Dong YD, Larson I, Barnes TJ, et al. Adsorption of nonlamellar nanostructured liquid-crystalline particles to biorelevant surfaces for improved delivery of bioactive compounds. ACS Appl Mater Interfaces 2011;3(5):1771-80.

[54] Mishraki T, Ottaviani MF, Shames AI, et al. Structural effects of insulin-loading into HII mesophases monitored by electron paramagnetic resonance (EPR), small angle X-ray spectroscopy (SAXS), and attenuated total reflection Fourier transform spectroscopy (ATR-FTIR). J Phys Chem B 2011;115(25):8054-62.

[55] Boyd BJ, Whittaker DV, Khoo SM, et al. Hexosomes formed from glycerate surfactants----formulation as a colloidal carrier for irinotecan. Int J Pharm 2006;318(1-2):154-62.

[56] Zeng N, Gao X, Hu Q, et al. Lipid-based liquid crystalline nanoparticles as oral drug delivery vehicles for poorly water-soluble drugs: cellular interaction and in vivo absorption. Int J Nanomedicine 2012;7:3703-18.

[57] Caltagirone C, Murgia S, Prodi L, et al. Drug-loaded fluorescent cubosomes: versatile nanoparticles for potential theranostic applications. Langmuir 2013;29(22):6673-9.

[58] Nguyen TH, Hanley T, Porter CJH, et al. Nanostructured liquid crystalline particles provide long duration sustained-release effect for a poorly water-soluble drug after oral administration. J Control Release 2011;153(2):180-6.

[59] Dian L, Yang Z, Li F, et al. Cubic phase nanoparticles for sustained release of ibuprofen formulation characterization and enhanced bioavailability study. Int J Nanomedicine 2013;2013:845-54.

[60] Gan L, Han S, Shen J, et al. Self-assembled liquid crystalline nanoparticles as a novel ophthalmic delivery system for dexamethasone: improving preocular retention and ocular bioavailability. Int J Pharm 2010;396(1-2):179-87.

[61] Han S, Shen J-Q, Gan Y, et al. Novel vehicle based on cubosomes for ophthalmic delivery of flurbiprofen with low irritancy and high bioavailability. Acta Pharmacol Sin 2010;31(8):990-8

[62] Vicentini FT, Depieri LV, Polizello AC, et al. Liquid crystalline phase nanodispersions enable skin delivery of siRNA. Eur J Pharm Biopharm 2013;83(1):16-24.

[63] Rizwan SB, Assmus D, Boehnke A, et al. Preparation of phytantriol cubosomes by solvent precursor dilution for the delivery of protein vaccines. Eur J Pharm Biopharm 2011;79(1):15-22.

[64] Rizwan SB, McBurney WT, Young K, et al. Cubosomes containing the adjuvants imiquimod and monophosphoryl lipid stimulate robust cellular and humoral immune responses. J Control Release 2013;165(1):16-21. This study optimizes the design of cubosomes containing protein-based vaccines to enhance immunogenic responses.

[65] Gordon S, Young K, Wilson R, et al. Chitosan hydrogels containing liposomes and cubosomes as particulate sustained release vaccine delivery systems. J Liposome Res 2012;22(3):193-204.

[66] Salonen A, Muller FO, Glatter O. Internally self-assembled submicrometer emulsions stabilized by spherical nanocolloids: finding the free nanoparticles in the aqueous continuous phase. Langmuir 2010;26(11):7981-7.

[67] Obayya S, Hameed MFO, Areed NF. Computational Liquid Crystal Photonics: Fundamentals, Modelling, and Applications. UK: John Wiley & Sons; 2016

[68] F. F. Xu, Y. J. Li, Y. Lv, et al., "Flat-panel laser displays based on liquid crystal microlaser arrays," CCS Chem., vol. 2, pp. 369–375, 2020.

[69] H. Yoshida, K. Inoue, H. Kubo, and M. Ozaki, "Phase-dependence of gold nanoparticle dispersibility in blue phase and chiral nematic liquid crystals," Opt. Mater. Express, vol. 3, p. 842, 2013.

[70] I. Dierking, W. Blenkhorn, E. Credland, et al., "Stabilising liquid crystalline blue phases," Soft Matter, vol. 8, pp. 4355–4362, 2012.

[71] N. Wang, J. S. Evans, J. Mei, J. Zhang, I.-C. Khoo, and S. He, "Lasing properties of a cholesteric liquid crystal containing aggregation-induced-emission material," Opt. Express, vol. 23, p. 33938, 2015.

[72] J. Justice, C. Bower, M. Meitl, M. B. Mooney, M. A. Gubbins, and B. Corbett, "Wafer-scale integration of group III-V lasers on silicon using transfer printing of epitaxial layers Nat," Photonics, vol. 6, pp. 610–614, 2012.

[73] M. Chapran, E. Angioni, N. J. Findlay, et al., "An ambipolar BODIPY derivative for a white exciplex OLED and cholesteric liquid crystal laser toward multifunctional devices," ACS Appl. Mater. Interfaces, vol. 9, pp. 4750–4757, 2017.

[74] A. Varanytsia, H. Nagai, K. Urayama, and P. Palffy-Muhoray, "Tunable lasing in cholesteric liquid crystal elastomers with accurate measurements of strain," Sci. Rep., vol. 5, 2015.

[75] H. Lu, C. Wei, Q. Zhang, et al., "Wide tunable laser based on electrically regulated bandwidth broadening in polymer-stabilized cholesteric liquid crystal," Photonics Res., vol. 7, p. 137, 2019.
[76] Z. Diao, S. Deng, W. Huang, et al., "Organic dual-wavelength distributed feedback laser empowered by dye-doped holography," J. Mater. Chem., vol. 22, pp. 23331–23334, 2012.
[77] J.-D. Lin, S.-Y. Huang, H.-S. Wang, et al., "Spatially tunable photonic bandgap of wide spectral range and lasing emission based on a blue phase wedge cell," Opt. Express, vol. 22, p. 29479, 2014.
[78] M. A. Rahman, S. Mohd Said, and S. Balamurugan, "Blue phase liquid crystal: strategies for phase stabilization and device development," Sci. Technol. Adv. Mater., vol. 16, 2015.
[79] W. Huang, D. Pu, W. Qiao, et al., "Tunable multi-wavelength polymer laser based on a triangular-lattice photonic crystal structure," J. Phys. D. Appl. Phys., vol. 49, 2016.
[80] D. Luo, Q. G. Du, H. T. Dai, X. H. Zhang, and X. W. Sun, "Temperature effect on lasing from Penrose photonic quasicrystal," Opt. Mater. Express, vol. 4, p. 1172, 2014.
[81] D. S. Wiersma and S. Cavalieri, "Light emission: A temperature tunable random laser," Nature, vol. 414, pp. 708–709, 2001.
[82] L. Ye, B. Liu, F. Li, Y. Feng, Y. Cui, and Y. Lu, "The influence of Ag nanoparticles on a random laser from dye-doped nematic liquid crystals," Laser Phys. Lett., vol. 13, 2016, https://doi.org/10. 1088/1612-2011/13/10/105001.
[83] V. D'Innocenzo, G. Grancini, M. J. P. Alcocer, et al., "Excitons versus free charges in organo-lead tri-halide perovskites," Nat. Commun., vol. 5, 2014.
[84] Q. Lin, A. Armin, R. C. R. Nagiri, P. L. Burn, and P. Meredith, "Electro-optics of perovskite solar cells," Nat. Photonics, vol. 9, pp. 106–112, 2015.
[85] P. J. W. Hands, D. J. Gardiner, S. M. Morris, C. Mowatt, T. D. Wilkinson, and H. J. Coles, "Band-edge and random lasing in paintable liquid crystal emulsions," Appl. Phys. Lett., vol. 98, 2011.
[86] A. Mahmood, V. Kavungal, S. S. Ahmed, et al., "Magnetic field sensing using whispering-gallery modes in a cylindrical microresonator infiltrated with ferronematic liquid crystal," Opt. Express, vol. 25, p. 12195, 2017.

[87] Ishihara S. How far has the molecular alignment of liquid crystals been elucidated? Journal of Display Technology. 2005;1(1):30.
[88] Scheffer TJ, Nehring J. Accurate determination of liquid-crystal tilt bias angles. Journal of Applied Physics. 1977;48(5):1783-1792.
[89] Wang Z, Cai S. Recent progress in dynamic covalent chemistries for liquid crystal elastomers. Journal of Materials Chemistry B. 2020;8(31):6610-6623. UK: Royal Society of Chemistry.