Abstract: The origin of biological homochirality, e.g., life selects the L-amino acids and D-sugar as molecular component, still remains a big mystery. It is suggested that mirror symmetry breaking plays an important role. Recent researches show that symmetry breaking can also occur at a supramolecular level, where the non-covalent bond was crucial. In these systems, equal or unequal amount of the enantiomeric nanoassemblies could be formed from achiral molecules. In this paper, we presented a brief overview regarding the symmetry breaking from dispersed system to gels, solids, and at interfaces. Then we discuss the rational manipulation of supramolecular chirality on how to induce and control the homochirality in the self-assembly system. Those physical control methods, such as Viedma ripening, hydrodynamic macro- and micro-vortex, superchiral light, and the combination of these technologies, are specifically discussed. It is hoped that the symmetry breaking at a supramolecular level could provide useful insights into the understanding of natural homochirality and further designing as well as controlling of functional chiral materials.

Keywords: symmetry breaking; assemblies; supramolecular chirality; homochirality; self-assembly; vortex

1. Introduction

Chirality is one of the fundamental properties found in nature and also vital in many fields, including chemistry, physics, biochemistry, pharmacy, and materials science [1–5]. The chirality of molecular components has dramatic consequences in life systems, where biological homochirality, e.g., L-amino acids and D-sugar are solely selected, still remains a big mystery [6,7]. It has a profound effect across a spectrum of disciplines in both industrial and academic researches [8,9]. Beyond the molecule level, the chirality is extended down to subatomic and up to supramolecular and higher hierarchical levels [10]. The biological DNA double helixes and helical proteins are the typical consequence of molecular chirality and formed via self-assembly at a supramolecular level. In these chiral nanostructures, the structural complexity, information storage, and the realization of complicated functions significantly related to the chirality. At a supramolecular level, many chiral or achiral molecules prefer to self-assemble into an asymmetric packing mode, thus we could detect supramolecular chirality from various combinations of chiral and achiral molecules [11,12]. Generally, the chirality can be expressed from the chiral molecules to the self-assembled assemblies via non-covalent bonds. For the mixed system including chiral and achiral building blocks, the chirality can be transferred from the chiral components to achiral components, and thus endowing the achiral molecules with supramolecular chirality. Apart from that, even exclusively achiral molecules can form chiral aggregates due to the symmetry breaking [13–17]. While in most of the cases, an equal amount of the right and left-handed assemblies appeared from achiral molecules, predominant chiral aggregates have also been found. However, while these systems are interesting, a great challenge remains in controlling the supramolecular chirality or achieving the homochiral assemblies from the stochastic distributions.
It is generally believed that homochirality is attained in consecutive steps: starting from a minute chiral bias, and a subsequent chiral amplification process for enantiomeric enrichment and chiral transmission from one set of molecules to another [18,19]. For the first stage, the chiral bias is usually generated by the symmetry breaking. For the second stage, amplifying chirality by using self-assembly is a well-known strategy in supramolecular assemblies [11]. Therefore, exploring the symmetry breaking in self-assembled nanoassemblies is crucial and inspired for the understanding the of biomolecular homochirality during the evolution of life [19–23].

In this review, we will firstly present a brief synopsis of symmetry breaking in self-assembled systems, including crystals, liquid crystals, air/solution and solution/solid interface, and supramolecular gels. After that, we pay more attention to the manipulation of supramolecular chirality in the self-assembled systems by physical or chemical ways such as adding chiral dopants, applying Viedma ripening, hydrodynamic macro- and micro-vortex, superchiral light, and the combination of these technologies. Those physical control ways are mostly discussed.

2. Symmetry Breaking in Self-Assembly Systems

Over the past two decades, spontaneous symmetry breaking has been found in various self-assembly systems including crystals [24–26], Langmuir monolayers [27–29], liquid/solid interface [30–32], liquid crystals [33–37], dye aggregates [14,16,38,39], amphiphilic assemblies [40,41], and supramolecular gels [42–47]. Figure 1 illustrates some typical examples in these field. One chiral crystal that has been investigated in detail is tartrate [48]. During crystallization process, two kinds of chiral crystals with almost identical physical properties can be formed. However, the plane of polarization rotates are different when linearly polarized light (LPL) passes through these chiral crystals. It should be noticed that their optical activity maintains when these crystals are dissolved in water. However, another well-studied crystal with chirality in solid, named as sodium chlorate (NaClO₃), behaves quite differently, as it displays optical activity in crystal state (Figure 1A), but the optical properties disappears when the crystal totally dissolves in solution [49,50]. It is known that a crystal exists in a molecular or ion state in solution. Therefore, the above phenomenon suggests that ions of tartrate molecules are chiral. Conversely, the ions of the NaClO₃ molecule are achiral. This is one typical example of symmetry breaking in crystal systems, and thereafter many achiral molecules have been found to be chiral in crystals [51–55].

Apart from a few reports of symmetry breaking in solution [16,38,56–59], the introduction of an interface is effective to control the intermolecular interactions, thereby affecting their self-assembly properties. The symmetry also can be broken at a confined two-dimensional (2D) surface/interface during the self-assembly of achiral building blocks [60]. In fact, the formation of symmetry breaking at a surface/interface is more common than chiral crystallization in three dimensions [61]. However, compared with the solution state, the analysis of assemblies at surfaces/interface can be more complicated. For example, the chiral domains are usually hard to distinguish and the artefacts can confound the optical spectroscopy measurements. Even so, the study of symmetry breaking on surfaces and at interfaces not only assists our understanding of three-dimensional crystallization and self-assembly process, but also provides insight into how to fabricate otherwise complicated chiral materials, such as chiral graphene nanoribbons [62,63].

Among many kinds of 2D materials, Langmuir–Blodgett (LB) technology is an effective method to orderly arrange molecules on the interface [64,65]. Figure 1B gives a novel type of chiral assemblies fabricated from achiral amphiphilic molecules, a derivative of barbituric acid [28]. This molecule could form a chiral LB films at the air/water interface. As shown in the atomic force microscope (AFM) images, this LB film was consisted of spiral nanoarchitectures. More interestingly, these spirals were found to wind in both an anticlockwise (CCW) and a clockwise (CW) direction, and a careful investigation indicated this morphology was closely depended on the surface pressure. It was noted that the H-bonding between barbituric acid derivatives themselves is crucial for the self-assembly. Specifically, the carbonyls in 4-and 6-carbonyl of the pyrimidinetrione could form H-bonds with the
hydrogen in the 1- and 3-N-H of the neighbouring pyrimidinetrione. Owing to the large aromatic rings and the directionality nature of hydrogen bonds between the amphiphilic molecules, the neighbouring molecules would incline from the same direction. Such aggregates gradually grow up to chiral fiber-like nanostructure, and then further curve in a fixed direction to form spirals [28].

Figure 1C shows another kind of 2D supramolecular chirality, which is observed at the liquid–solid interface [66]. With the support of scanning tunnelling microscopy (STM), the chirality properties of 2D molecular organization can be clearly observed with high resolution under extreme conditions [30,68,69]. Surface-confined nanoporous assemblies, such as a periodic mesh of nanowells shown in Figure 1C, represent one special kinds of monolayers. The chirality of this monolayer is distinguished according to the molecular models of interdigitation motifs. Figure 1C gives the typical STM image of the honeycomb architectures from achiral molecules at the 1-phenyloctane/graphite interface. Clearly, the CW and CCW rotation of nanowells (indicated by white line) could be observed. The alkyl chain
interdigitation interactions between neighbouring molecules at the liquid–solid interface were found to be crucial for the fabrication of the porous network structures [66].

In liquid crystal systems, there are many pioneering works that leading the research of symmetry breaking [33,35,70,71]. This is because liquid crystal is one unique phase that lies in between the crystals (or solid) and diluted solution. Different from the crystals, the weak intermolecular interactions in liquid crystal indicates that the driving force for chirality (long-range helical order) is relative weaker. On the other hand, the short-range chirality in liquid crystals is retained compared with the solution state. This combination leads to many distinct features, such as stimuli-responsive, self-healing, and adaptive behavior, which makes liquid crystals as the quintessential materials for self-assembly and symmetry breaking [72–74]. As shown in Figure 1D, when the crossed analyser and polarizer were slightly rotated, two kinds of domains are observed in some of the cubic phases [34]. Remarkably, when the rotation of the analyzer is reversed, the darker and brighter domains could exchange their contrast. However, the contrast does not change when the sample is rotated between the fixed polarizers, indicating that these domains belongs to a chiral structure with opposite handedness [34].

Recently, many achiral molecules, particularly the C3-symmetric structure molecules, are found to form helical assemblies in supramolecular gel systems [45,75]. For example, as shown in Figure 1E, chiral symmetry breaking phenomena are observed in the supramolecular gel of achiral benzene-1,3,5-tricarboxamide/tricarboxylate-based molecules [43,46,67]. The directional H-bonds between amide groups and the π−π stacking of the benzene rings are the main driven force during self-assembly process. When three non-chiral ethyl cinnamates were connected to the central benzene-1,3,5-tricarboxamide, the molecule was found to form instant gels with unequal number of right (P) and left (M)-handed twists, as observed from the scanning electron microscope (SEM) images in Figure 1E [43]. If the sample has more M-type twists than P-type twists, a negative Cotton effect was observed from the circular dichroism spectra; this was reversed if there were a relatively larger amount of P-type twists. Therefore, the uneven symmetry leads to the bulk macroscopic chirality of the supramolecular gels.

Based on the experimental data and the molecular dynamics simulation, it shows that the aggregation of these achiral C3 molecules could initially form predominantly P-type or M-type aggregates with a random distribution. Thereafter, due to the steric hindrance caused by the closing-molecular packing, the subsequently growth of those small helical aggregates will follow the original chirality to form one-dimensional helical aggregates. Finally, such unequal numbers of P-type and M-type helical aggregates further twisted into twisted ribbons or larger helical fibers and intertwined with each other to hold the solvent [43].

It should be noted that appropriate manipulation of different noncovalent interactions can fabricate chiral ordered structures with various dimensions and complexities, which might be comparable with that found in nature systems. Among these noncovalent interactions, the hydrogen bond (H-bond) is crucial due to its directionality, strength, specificity of the interaction, and biological relevance [76–80]. For example, as shown in Figure 2A, 2,4-Diamino-6-phenyl-1,3,5-triazines with a single oligo (ethylene oxide) chain could form an optically isotropic mesophase [81]. This achiral molecule first formed a primarily double-hydrogen-bonded dimeric aggregates, and these aggregates paralleled side-by-side, leading to a highly ordered and hydrogen-bonded aromatic bilayer structures. Interestingly, the ethylene oxide chain at both ends prohibits the parallel alignment of the hydrogen-bonded cores, and thus induces a small helical twist between them. After that, the helical deformation of the bilayer ribbons is formed. The results shown that hydrogen bonding leads to chiral aggregates that undergo long-range chirality synchronization in the isotropic bulk state [81].
Besides the hydrogen bond, there are a number of examples of dative-bond (coordination bond) driven symmetry breaking [82–86]. Figure 2B shows a novel coordination polymer gelators that stemmed from the coordination of Ag(I) and the achiral imidazole derivative [17]. Optically transparent gels could be formed when a methanol solution of the achiral monomer to an aqueous solution of silver nitrate at a 1:1 ratio of ligand: AgNO$_3$. The AFM measurements further revealed a well-developed network structure composed of fibrous aggregates. In addition, the zoomed-in image indicated that this thicker fiber consisted of a bundle of helical tubes. The CD spectra also exhibited mirror-imaged signals from different batches, indicating that chiral symmetry breaking is occurred during the coordination process. Due to the strong directional interactions between the rigid bent bridging ligands and Ag(I), the initial metal–ligand complexes with accidental excess of one helical direction were formed. Thereafter, the new aggregates would follow the same handedness to form a secondary helical structure. On the other hand, the formation of opposite helical aggregates is suppressed. Therefore, the eventual macroscopic chirality is observed [17].
As shown in Figure 2C, symmetry breaking that driven exclusively by weak $\pi-\pi$ interaction is studied in supramolecular assemblies [44]. An achiral $C_3$-symmetric gelator was found to form organogels in cyclohexane. Interestingly, the supramolecular gels were optically active with the helical nanofibers with predominant handedness. Since there are no any other noncovalent interactions in this system, the experiment results proved that purely $\pi-\pi$ stacking can also drive the symmetry breaking in the supramolecular gel system. In this case, $\pi-\pi$ interaction between benzene rings and cinnamate substituents were strong enough to form an overcrowded molecular packing. It is supposed that the achiral molecules could initially generate two kinds of helical conformer by chance, and subsequently grow up to form longer one-dimensional helical aggregates by following the original chiral conformation. At last, several helical aggregates further twisted into helical fibers [44].

In fact, combined noncovalent interactions including hydrogen bonding, electrostatic interaction, and $\pi-\pi$ stacking are generally necessary in most of the symmetry breaking systems. For example, both the hydrogen bonding and electrostatic interaction is essential in the fabrication of chiral tetraphenylporphyrin sulfonate (TPPS) aggregates [14]. Another example is the self-assembled achiral partially fluorinated benzene-1,3,5-tricarboxamides in solution, in which the 3-fold hydrogen bonding and dipole–dipole interaction play important roles [42].

3. Selection and Control of Supramolecular Chirality during Symmetry Breaking: Towards the Homochirality in Nanoassemblies

Even though the origin of chirality and homochirality in biological systems is still controversial, the quest to unravel this mystery has led to an intense research to select and control the supramolecular chirality during symmetry breaking. Actually, the manipulation of chirality in exclusive achiral systems can be much more useful, since it could not only provide a better understanding of the complicated biosystems, but also offer guidance on how to rational design of biomimetics as well as advanced chiral materials [87,88]. To date, various strategies such as changing pH [89], electroweak interaction [90,91] and microfluidic conditions [92,93], catalysis at prochiral crystal surfaces [94,95], adding chiral additive [96–99], applying circularly polarized light [100–102], rotational and magnetic force [103], and vortex and stirring motion [14,104–108], etc. are known to control the emerging chirality during symmetry breaking.

Generally, based on sergeant and soldier rule, adding chiral substance into the symmetry breaking systems is quite efficient and usual to control the macroscopic chirality [99,109,110]. For example, in the $C_3$ supramolecular gel system, a suitable amount of $(R)$-1-cyclohexyl ethylamine could result in the formation of $M$-type twists with a strong negative CD signal [43]. On the contrary, $(S)$-1-cyclohexyl ethylamine led to the $P$-type twists and a mirror-imaged CD spectrum. Owing to the interaction between amines and ethyl cinnamate, the added chiral amines achieved the chirality control through the ester–amide exchange reaction. In this case, the chiral amines could not completely remove from the system [43]. However, if the chiral dopants were replaced to chiral solvent, such as limonene and terpinen-4-ol, the induced chirality of the supramolecular gels could be maintained even after completely removing the chiral solvents [44].

In the solid state such as crystal systems, it is easier to achieve the chiral discrimination. Particularly, this applies to the crystallization process when the same enantiomers have a stronger interaction than that of the opposite enantiomer. Such kind of crystal is generally called as conglomerate crystals, representing that each crystal is homochiral (Figure 3A). In the words, the conglomerate can be regarded as a physical mixture of enantiomerically pure crystals of two kinds of enantiomer. However, only approximately 5–10% of chiral crystalline molecules belong to this case [9]. For the rest of approximately 90–95%, both enantiomers exist in one crystallographic unit cell, and the solid is called a racemic compound, racemate crystals, or true racemate. This is because the opposite enantiomers have a greater affinity than the same enantiomer in this case.
It is worth noting that applying stirring during crystallization is usually effective to break the symmetry, leading to a high enantiomeric excess of the resulting crystal [25,111,112]. In 2005, Viedma demonstrated that the initially racemic mixture of NaClO₃ crystals could completely transform into one chiral form over a period of several days (Figure 3B) [113]. Remarkably, the completely transformation means that the whole system achieves homochirality although the final handedness could not control. This transformation process, which is now called Viedma ripening, involves the deracemization of solid-to-solid and solution-to-solid [114,115]. The novelty of Viedma’s experiment lies in the addition of glass beads and magnetic bar during deracemization. The glass beads enhanced the grind of crystals, resulting in numerous small fragments with the identified handedness. Therefore, the homochirality is achieved by applying stir and grind for a period of time. It should be noted that the chiral bias can be controlled by crystal enantiomeric excess [113]. For example, solutions with initial 5% L-crystal enantiomeric excess give rise to 100% L-type crystals, and vice versa. Since that, this method was successfully extended to many crystal systems, and even organic reaction which contains crystal products. Very recently, Viedma ripening found broad applicability [18,116–122]. Without grinding treatment, a temperature gradient which involves several cycles of rapid heating and slow cooling could also realize the deracemization [123,124].

The responses of achiral molecules and its chiral assemblies to external stimulation can be also used to manipulate the supramolecular chirality after symmetry breaking. The J-aggregates of achiral amphiphilic porphyrins, such as 4-sulfonatophenyl and arylmeso-substituted porphyrins, may be the most representative model for the study of hydrodynamic forces [106,125]. Figure 4 illustrates the ground-breaking work of Ribo et al. in which the chiral signal of porphyrin aggregates can be controlled by vortex motion during self-assembly process [14]. The self-assembly of the achiral monomeric species were promoted by the rotary evaporation of very diluted solutions of deprotonated porphyrins.

Clearly, the randomly distributed chiral signals indicates that the unstirred experiments belong to a pure symmetry breaking process (Figure 4A). However, as shown in Figure 4B, the chiral selection was dependent on the rotation direction when the samples were applied rotary evaporation treatment. The statistical distribution indicated that 85% of the chiral signals could be controlled by the rotation direction, suggesting a biased symmetry breaking (Figure 4B). Due to the existence of anionic sulfonato groups and the positively charged porphyrin rings, the J-aggregation was achieved by the intermolecular electrostatic and hydrogen bonding interactions. Therefore, the arrangements of achiral porphyrins with different angles are indeed possible (Figure 4C). The schematic illustration shows that the chirality may be transferred from the macroscopic chiral force to the electronic distribution. After this report, the acting chiral hydrodynamic shear force during rotatory evaporation were theoretically investigated, and similar conclusions has been obtained in other type of vortices [126–129].
As a kind of the excited-state optical activity, circularly polarized light (CPL) has triggered intense research interests due to their potential applications in optical sensors [130,131], 3D displays [132,133], bioencoding [130,134,135], encrypted transmission, and storage of information [136], chiral catalysts [137–140], and photoelectric devices [141]. However, due to the small anisotropy factors (<10^{-5}), the obtained enantiomeric excess in most cases of asymmetric photolysis and photosynthesis is undesirable (<4%) [142,143]. When two counter-propagating CPL are interfered with opposite handedness, with different intensity but the same frequency, the generated light, which is called superchiral light (SCL), was demonstrated experimentally to enhance the enantioselective polymerization of achiral diacetylene monomer [144].

Figure 5A shows the experimental set-up for the generation of SCL from two CPL beams (325 nm) [144]. Clearly, compared with the conventional CPL, the achiral benzaldehyde-functionalized diacetylene (Figure 5B) LB films that irradiated by the SCL exhibited a stronger CD signal. In contrast, if the sample was polymerized by LPL, no signal was observed from the CD measurement (Figure 5C). As a result of the enhanced optical dissymmetry, the polydiacetylene films achieved in SCL field shows nearly 5-fold enhancement in dissymmetry factor. As illustrated in Figure 5D,E, compared with CPL irradiation, the enhanced optical dissymmetry in SCL may lead to more helical polydiacetylene (PDA) chains, thus resulting in an increased dissymmetry factor of PDA films. In addition, transmission electron microscopy (TEM) images also demonstrated that samples polymerized by SCL have more helical PDA chains than those polymerized with CPL [144].

Although all of the above approaches can be used alone to select the supramolecular chirality, not all of them are effective, due to their own limitations. In fact, a large number of reports employed more than one treatment to control the chirality of symmetry breaking [145]. For example, as shown in Figure 6A, Vlieg et al. demonstrated that the CPL irradiation caused symmetry breaking of an amino acid derivative could be amplified by a grinding process [146]. Specifically, a solid–liquid mixture was firstly irradiated with L- or R-CPL for 70 h (0.3 mW intensity). Thereafter, the slurry was grinded with a magnetic stirring bar and glass beads. In addition, organic base such as 1,8-diazabicyclo [5.4.0] undec-7-ene (DBU) was added in order to induce the racemization in solution. Five days later, the final chirality of enantiopure solid was found to be selected by the handedness of CPL. From the above
description, it can be concluded that a non-racemizable chiral photoproduct may be formed under the effect of the CPL irradiation, while the subsequent grind treatment amplified the small initial chirality [146].

Figure 5. (A) Experimental set-up for the generation of superchiral light (SCL) field. (B) The molecular structure of achiral benzaldehyde-functionalized diacetylene. (C) CD spectra of polydiacetylene films polymerized by (i) left-handed or (ii) right-handed SCL; (iii) left-handed or (iv) right-handed circularly polarized light (CPL); (v) linearly polarized light (LPL), respectively. Schemes and corresponding transmission electron microscope (TEM) images for the helical PDA chains prepared by using (D) CPL and (E) SCL irradiation, respectively. Reprinted with permission from ref. [144].

Figure 6B gives an example of how the relative directions of rotation and effective gravity control the chirality of supramolecular assemblies constructed by achiral tris-(4-sulfonatophenyl) phenylporphyrin (TPPS3) [103]. In order to simultaneously realize the manipulation of rotational, gravitational and orienting forces, an experiment set-up is designed and outlined in Figure 6B. To be brief, this set-up contains a tube with seven cylindrical vessels. Each of them was positioned at different positions and rotated for various time. Such a set-up ensures a solid-body rotation, and thus avoids the creation of pseudovortices. The rotation is characterized by two parameters, one is the angular momentum (L), which is set by CW or CCW rotation viewing from the top. The other factor is effective gravity (G_eff) that related to the magnetic levitation force. After rotation treatment, these samples were placed outside the magnet for three days before the CD measurement. The handedness of the aggregates is found to depended on the relative directions of the rotational and gravitational forces applied. For example, the antiparallel L and G_eff results in a positive CD signal, while parallel L and G_eff leads to the opposite signals. Further study revealed that the nucleation step was crucial to control the final handedness. On the basis of these experimental results, a possible schematic model was proposed. As a result of the electrostatic and π-stacking interactions, the TPPS3 molecules could aggregate into small chiral nucleus. During this period, the hydrodynamic flow consistently applied. Meanwhile, the magnetic field arranges the nuclei along the rotation axis, which eliminated the randomizing Brownian motion and thus achieved the controlled chirality. After that, chiral nuclei worked as chiral seeds, and the subsequent growth followed the initial chirality even after the external stimulation was ceased [103].
randomizing Brownian motion and thus achieved the controlled chirality. After that, chiral nuclei worked as chiral seeds, and the subsequent growth followed the initial chirality even after the external stimulation was ceased [103].

Samples that obtained from two outlets always exhibited mirror-imaged CD signals. The unique feature of microvortices is the strong shear gradient, which allows the chiral alignment and formation of the supramolecular oligomer chain. The dual effect of LPL and magnetic field might orient the helical oligomer chain in a chiral arrangement, which is benefit for the polymerization of closing monomer. Therefore, the final predominant helical chains can be directed by the relative orientation of LPL and magnetic field [137].

Compared with CPL, the application of LPL irradiation is usually neglected. However, combined with other physical force, such as magnetic field, LPL is also effective to control the enantioselective polymerization of diacetylene derivative (Figure 6C) [137]. As a result of the magnetochiral dichroism effect, the achiral building blocks could selectively form one-handed helical oligomer chain. The dual effect of LPL and magnetic field might orient the helical oligomer chain in a chiral arrangement, which is benefit for the polymerization of closing monomer. Therefore, the final predominant helical chains can be directed by the relative orientation of LPL and magnetic field [137].

Very recently, inspired by natural rock micropores (Figure 7A), a microvortex generated by a microfluidic device was demonstrated to control the chirality after symmetry breaking either in gel or solution states [93]. Computational fluid dynamics (CFD) simulation suggested that the CCW and CW laminar vortices could be generated by the mismatched flow velocities between the main channel and the microchambers, and the microvortices in the left and right microchamber are predominantly P and M chirality, respectively. In addition, the high-speed microscopic observation showed that the highest rotation speed could be $4 \times 10^4$ rpm in this device. When the achiral building blocks (BTAC and TPPS$_4$) were injected into the microfluidic device, microvortex-induced symmetry breaking of these achiral molecules leads to the formation of supramolecular gels or TPPS$_4$ nuclei. Samples that obtained from two outlets always exhibited mirror-imaged CD signals. The unique feature of microvortices is the strong shear gradient, which allows the chiral alignment and formation of the supramolecular nuclei against the Brownian regime during the mirror symmetry breaking process. The microvortice controlled nuclei could be subsequently amplified into supramolecular aggregates with a certain
chiral bias. As a result, the chirality distribution suggested the microvortices maintained 96% chirality control [93].

Compared with crystals, the homochirality after symmetry breaking is more difficult to achieve in soft matter and solution due to the dynamic features. In addition, the good stability of chiral assemblies is also essential. For example, the exchange between the monomers and helical aggregates is usually fast in dilute solution [99]. Figure 7B illustrated a novel strategy for obtaining almost homochiral supramolecular assemblies with controlled handedness in a totally achiral system [67].

Due to the hydrogen bond and π-π stacking, the achiral C₃ molecules could form instant gels in a mixed solvent of DMF/H₂O. However, the common gelation process only achieved racemic gels. Interestingly, applying vortex mixing during self-assembly process could significantly amplified the supramolecular chirality, leading to near-unity homochiral assemblies. In this case, the chiral signals could be further amplified in the following growth. More importantly, by using a small amount of assemblies obtained as chiral seeds, a supramolecular ripening process could transform the racemic gels to the homochiral state with the seeds. Therefore, no additional chiral substances are required to obtain both chirality controlled and homochiral assemblies [67].

![Figure 7](image-url)

**Figure 7.** (A) Schematic hypothesis of the origin of supramolecular chirality in nature. (a) The imitated microvortices that generated by the microfluidic device. (b) Computational fluid dynamics (CFD) simulation of the chiral microvortices. Formation of chiral supramolecular assemblies of achiral (c) (tris (ethyl cinnamate) benzene-1,3,5-tricarboxamide (BTAC) and (d) tetraphenylporphyrin (TPPS4) and C₂mim⁺ ionic stabilizer within the microvortices. Reprinted with permission from ref. [93]. (B) Vortex mixing-accompanied self-assembly induced homochiral supramolecular assemblies from exclusively achiral molecules. (a) Schematic illustration of the procedures towards homochirality. (b) Red curve: the absolute dissymmetry factors (gCD) of the samples prepared with different vortex times; blue curve: the correlation between the absorption data and cooling time. (c) SEM images of the helical structures after vortex mixing. (d) Schematic illustration of the mechanism towards homochirality. Reprinted with permission from ref. [67].
4. Conclusions

Symmetry breaking in self-assembled systems is an interesting phenomenon leading to an understanding of the homochirality in a biological system and providing an important method towards the construction of functional chiral materials, which significantly extend the potential applications of achiral building blocks. This review provides a summary and discussion of symmetry breaking based on the diverse systems from solution, interfaces to solids and gels. Moreover, we present a brief synopsis on the selection and control of supramolecular chirality in the self-assembled systems from achiral molecules. A number of novel physical manipulations, such as superchiral light field, microfluidic device induced microvortex, and vortex mixing have been successfully used to achieve the chiral selection/synthesis and even homochirality of nanoassemblies.

Despite these achieved developments in symmetry breaking, advanced techniques are still needed to follow the symmetry breaking process and the amplification of the supramolecular chirality from completely achiral molecules. For most of the systems, even though we could observe the microscopic chirality from the CD or CPL spectra and morphology, two enantiomers coexisted after symmetry breaking. Therefore, it is also necessary to quantitatively analyze the enantiomeric excess of the supramolecular assemblies although it is dynamic in many cases.

So far, various possibilities have been proposed to explain the emergency of the initial chiral bias in biomolecules [101,147–149]. However, these results are controversial [19,150]. On the other hand, attaining homochirality is still a challenge in exclusively achiral systems. In general, asymmetric environments or elements are necessary for the chirality control of symmetry breaking. Macroscopic chiral force caused by stirring or vortex mixing may transfer the chirality into the asymmetry molecule aggregation. Although many methods were discovered to control the chirality, the combination of two or more processes is more effective to the selection and subsequent amplification the supramolecular chirality during symmetry breaking towards the homochiral assemblies, which may enlighten the understanding of biomolecular homochirality during the evolution of life.

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