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Liquid-based materials

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Advanced materials are the material basis for social development. Solid materials have the characteristics of stability, durability, and processability, but it is often difficult for them to have a large-scale and rapid dynamic response [1]. Liquid materials are usually smooth, defect-free, and self-healing, with dynamic response and high mass transfer efficiency, but they cannot be self-supporting and are unlikely to be fabricated into fixed shapes themselves [2,3]. Liquid-based materials are rising for breaking the limitations of conventional materials. They are composed of solids and liquids, which endows them with the characteristics of both solid and liquid materials and unique advantages in fast dynamic response, soft interface, structural plasticity, etc. [2–6]. The solid materials offer frameworks and confinements for stabilizing liquid materials. Based on the structure types, the solid framework in the liquid-based materials can be roughly divided into the non-supporting structure, soft supporting structure, and hard supporting structure, although in some conditions, coupled structure types exist (Figure 1). Various liquids with different properties including water-based liquids, organic liquids, ionic liquids, liquid metals, and other responsive liquids have been widely used [6–10].

In fact, liquid-based materials are ubiquitous in nature. For example, the surface of the peristome of some carnivorous plants is completely covered with a liquid layer, forming a super-smooth surface; the liquid film on the eyes provides us with a very smooth refractive surface and makes us adjust the refractive index of the liquid film, and also isolates dust and bacteria to protect the eyes; the synovial fluid in the knee gap plays a central role in reducing joint wear during the hundreds of millions of times of friction in its lifetime [5]. In essence, liquid-based materials can bring new interfacial physical and chemical properties to traditional solid materials [1,5]. Simultaneously, that dynamic interaction between the liquid and the solid is utilized to carry out the functional interface physicochemical design between the liquid and the solid, providing a broader space and unlimited design possibilities for breaking through problems that traditional materials cannot solve [2].

In recent years, various kinds of liquid-based materials have been developed, such as hydrogels [7], ionic liquid-based materials [6], liquid metal-based materials [9], liquid-infused surfaces [8], and liquid-based

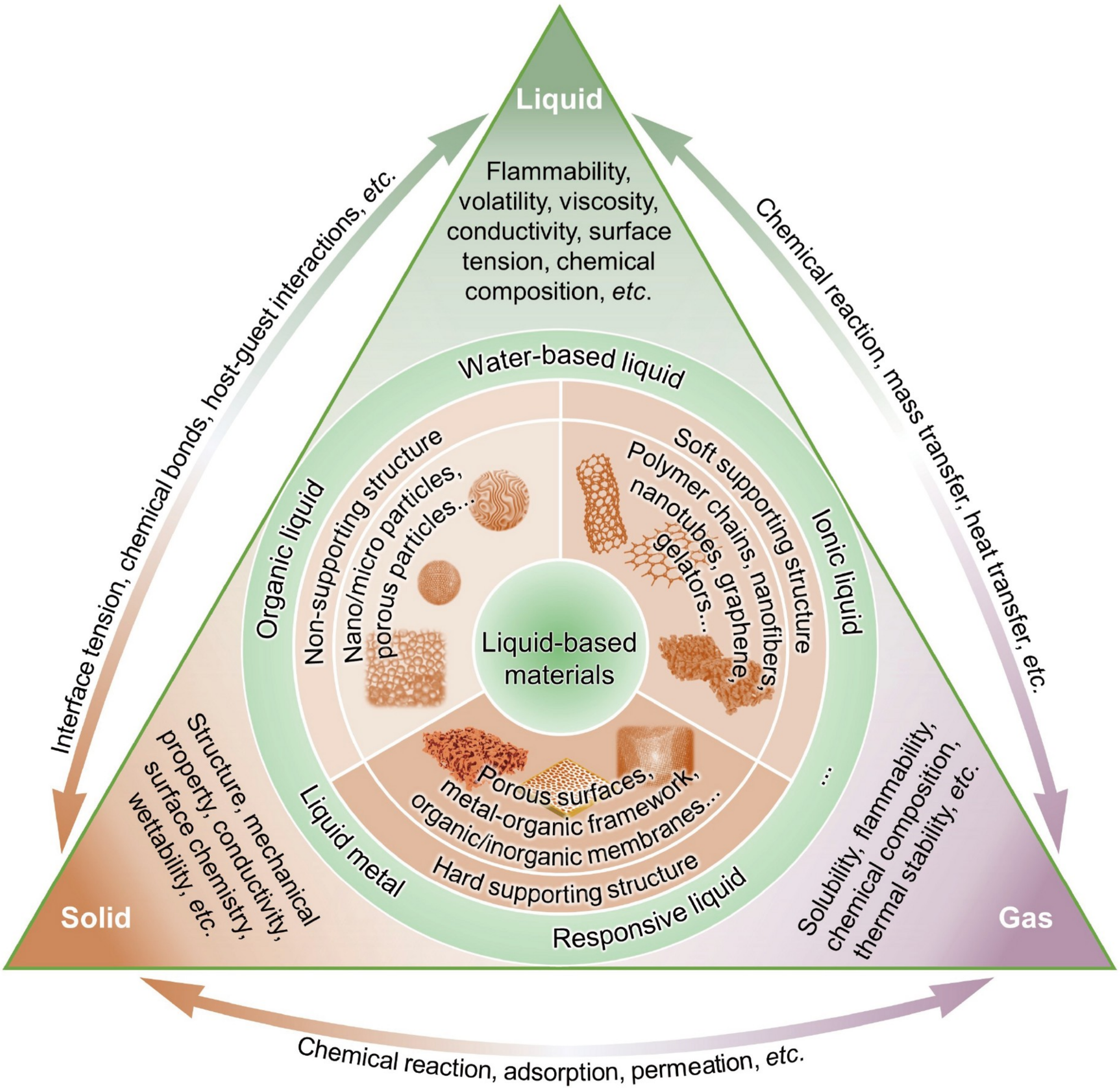

Figure 1 Design of liquid-based materials and the typical interactions at the interface among the solid/liquid/gas interfaces. The middle circles show the liquid-based materials design by selecting and designing two essential components, including the solid part and the liquid part. The light brown circle shows the typical solid parts, which can be divided into three categories according to the structural role they play. The green circle shows the typical liquid parts. Three-phase characteristics that need to be considered when designing liquid-based materials are located at the three corners of the triangle. These characteristics are not only the factors to be considered in the construction of liquid-based materials but also the external factors of the environment in which the liquid-based materials are used. The arrows represent the interactions at solid/liquid, gas/solid, and liquid/gas interfaces inside or outside the liquid-based material.

membranes [3]. These liquid-based materials have attracted more and more attention in many fields, because of their significant advantages in adaptability, anti-fouling, anti-ice, anti-fog, self-healing, defect-free, and high interface transport efficiency [2–5]. For the non-supporting structure solid framework, the solid part is usually particle materials, such as nano/micro particles and porous particles, and this kind of liquid-based materials generally still has fluid ability. For example, Dunne *et al*. [10] realized liquid-in-liquid fluidic channels by immiscible magnetic liquid-based material containing magnetic particles, which show nearfrictionless, self-healing, anti-fouling, and non-clogging properties. The solid materials used as soft supporting structures generally include polymer chains, nanofibers, nanotubes, graphene, and gelators, which provide soft and deformable skeletons and expand the scope of application. For example, Markvicka *et al*. [9] developed a soft and highly deformable circuit interconnect material architecture composed of liquid metal droplets suspended in a soft elastomer, which exhibited unprecedented electronic robustness in a self-healing soft robotic and self-repairing digital counter after significant damage. Zhang *et al*. [11] used hybridizing polyelectrolyte hydrogel and aramid nanofiber membrane to build a three-dimensional gel interface to achieve high-performance osmotic energy conversion. Choi *et al*. [12] fabricated a hydrogel liquid metal composite using three-dimensional printed molds and demonstrated the feasibility of reliable utilization of a hydrogel and liquid metal in self-healing electronics. The hard supporting structure built by the solid part usually provides a three-dimensional structure to hold the liquid, like porous surfaces, metal-organic framework, and organic/inorganic membranes, while there are also multiple structure combinations in one liquid-based material. Li *et al*. [13] enhanced the separation efficiency of carbon dioxide and water vapor using a superb water permeable membrane prepared by treating an alumina hollow fiber supported metal-organic framework membrane with a hydrophilic ionic liquid. The slippery liquid-infused porous surface constructed by Villegas *et al.* [4] and Aizenberg and collaborators [5] inspired by pitcher plants shows excellent anti-fouling, anti-ice, anti-bacteria, anti-thrombosis, and anti-fog properties. Hou *et al*., inspired by the alveoli, established a liquid gating system based on membrane science and technology [14] and proposed "liquid gating technology" [2]. This technology expands the fundamental scientific issues of the traditional membranes from the solid-liquid and solid-gas interfaces to the solid-liquid-liquid and solid-liquid-gas interfaces and can be applied with a dynamic physicochemical interface design for the application in multiphase separation, electroless visual substance detection, biomedical catheters, responsive switchable gas valves, and other fields [2]. Most recently, a continuous air purification system is developed based on liquid-based materials. In this system, the liquid gating solid matrix was used to filtrate the particles and control the gas-liquid-solid multiphase interaction property by adjusting the redox state, and the gating liquid as functional material is also used to absorb the particles in the air. Through the coordination of the two parts of the system, the good anti-fouling performance and long-term purification can be achieved [15]. In 2020, liquid gating technology was selected as the top ten emerging technologies in the chemistry of the year by the International Union of Pure and Applied Chemistry (IUPAC). IUPAC points out that "*Liquid gates can selectively process mixtures of fluids without clogging… they could become extremely useful for large-scale filtration and separation processes… liquid gates could accelerate the progress towards SDG 6*, *which looks to ensure access to clean water and sanitation for all… since liquid gates require no electricity at all*, *they ensure huge energy savings… liquid gates will soon be scaled-up and adopted by key players in the chemical enterprise*" [16]. Although liquid-based materials have shown great advantages in many fields, how to design and prepare more controllable, stable, and responsive liquid-based materials, how to break through the preparation theory and technology of liquid-based material systems around the key scientific issue of two-phase or multiphase interfaces control among solid, liquid, and gas and interactions is still a great opportunity and challenge for liquid-based materials in the future.

Despite solid materials and liquid materials commonly used having met basic social needs, many new materials are still urgently needed in the key fields to meet the social development goal in the near future, e.g., the efficient adsorption and catalytic materials needed to achieve carbon neutrality. New concepts and methods are used to break through the preparation theory and technology and understand the relationship between macroscopic properties and microscopic mechanisms of liquid-based materials. This is due to the complexity of liquid and liquid-based materials, and further studies on this aspect are required [17]. The advantages of the liquid in terms of molecular scale dynamic response, a functional structure in a microscopic or limited domain space, the designability of the structure of a solid matrix, and the mass, momentum, energy transport and reaction at the interface all need to be considered. Additionally, liquid-based materials can also be combined with artificial intelligence, machine learning, and materials genome initiative, which have emerged in recent years, to further explore the interaction between solids and liquids, expand the design of the materials, improve their properties, and ensure their stability. This will bring new ideas for smart applications of liquid-based materials, such as substance detection, interface transport, energy conversion and storage, microfluidics, artificial organs, and wearable devices in the areas of ecological environment, manufacturing technology, resources and energy, agricultural science and technology, life and health, and aerospace science and technology.

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Author contributions

X.H. conceived the idea. Y.Z. and X.H. wrote the manuscript and approved the submission of the manuscript.

Conflict of interest

The authors declare that they have no conflict of interest.

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