Engineering Capillarity: Porous and structured materials for fluid management

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Abstract. Capillary action, traditionally observed in natural systems such as plant xylem or fibrous tissues, has emerged as a design principle in modern materials science. This review surveys natural, engineered, and advanced materials that exploit capillarity for fluid management, with emphasis on structure–property–performance relationships. We classify materials into fibrous networks, foams, lattices, ceramics, polymers, and composites, highlighting how their pore size distributions, connectivity, and wettability govern both capillary pressure and permeability. Application-driven designs are examined in heat pipes, evaporative cooling systems, paper-based diagnostics, biomedical dressings, and capillary-active building materials. Particular attention is given to strategies that overcome classical trade-offs-bilayer wicks, graded porosity, hierarchical structures, and patterned wettability-demonstrating that strong suction and high permeability can coexist. From these examples, general design rules are derived that link pore geometry and porosity to measurable performance metrics. Looking forward, adaptive and multifunctional capillary materials, including smart hydrogels, nanostructured surfaces, and bio-derived aerogels, are expected to redefine how fluids are transported, regulated, and sensed in next-generation technologies. We argue that engineering capillarity constitutes a unifying paradigm for fluid management across disciplines, enabling new opportunities in energy, healthcare, and sustainable construction.

INTRODUCTION

Capillarity-the spontaneous movement of liquids through narrow channels and porous structures driven by surface tension and adhesive forces-is a fundamental transport mechanism in both natural and engineered systems. It governs water movement in soils, xylem transport in plants, and imbibition in fibrous tissues, while also enabling technologies such as heat pipes, evaporative cooling devices, diagnostic microfluidics, and porous building materials. The common principle is that pore size, porosity, and surface wettability dictate the balance between capillary pressure (favoring liquid rise) and permeability (governing flow rate) [1-2].

Natural materials such as cotton, paper, and wood have long exploited capillarity [3] for fluid absorption and transport, but these lack durability, structural precision, and tunability. In contrast, engineered porous materials-including ceramics, sintered metals, and polymer composites-offer the ability to tailor pore geometry, surface chemistry, and hierarchical structure for targeted performance[3-4]. More recent advances in additive manufacturing and surface nanostructuring have enabled the creation of gradient, bilayer, and bio-inspired architectures that combine high capillary pressure with high permeability, overcoming classical trade-offs [5, 6].

Applications increasingly drive the design of capillary materials. For example, loop heat pipes and vapor chambers demand fine pores to sustain liquid return against gravity while preserving permeability [1,3]. Microfluidic diagnostics rely on precisely dimensioned channels and surface chemistries to control flow rates and detection sensitivity [7,8] Building materials leverage capillarity to buffer indoor humidity, while biomedical dressings require controlled uptake and sustained release of fluids [9]. Across these fields, capillarity is evolving from a passive phenomenon to an engineered design principle.

EXPERIMENTAL RESEARCH

Concept of Capillarity in Materials; Capillarity arises from the balance of surface tension, liquid–solid adhesion, and gravitational forces. In its simplest form, Jurin's law describes the height h of a liquid column in a capillary tube of radius r:

$$h = \frac{2\gamma cos\theta}{\rho g r} \quad (1)$$

where γ is surface tension, θ- the contact angle, ρ- liquid density, g- gravitational acceleration, and r- the radius of the capillary [1]. This highlights the inverse relationship between pore size and rise height. This highlights the inverse relationship between pore size and rise height. When extended to porous media, parameters such as pore geometry, connectivity, wettability, and tortuosity become critical. Fine pores enhance capillary pressure but reduce permeability-a fundamental trade-off in design [2, 10]. These systems are further complicated in soft porous solids, where deformation and swelling under capillary action alter fluid transport [11]. More complex models-such as those discussed in reviews on capillary imbibition—take into account irregular geometries and dynamic effects like meniscus advancement, contact line pinning, and geometry-induced hysteresis [12] . Similarly, flow through low-density fibrous media, is governed by pore orientation, fiber arrangement, and saturation levels [13]. In engineered systems, material architecture is designed to optimize capillarity. Polymer wick structures, for example, must balance pore size (for capillary pressure) and permeability to sustain flow for microfluidic systems, fuel cells, and cooling applications [14]. Meanwhile, bi-porous aluminum wicks enhance capillary pressure via a dual-pore network, addressing the classic trade-off between pressure and permeability [10]. Lastly modeling approaches for heat pipes with capillary wicks provide engineering insights on how pore geometry affects temperature gradients, flow stability, and thermal performance [15].

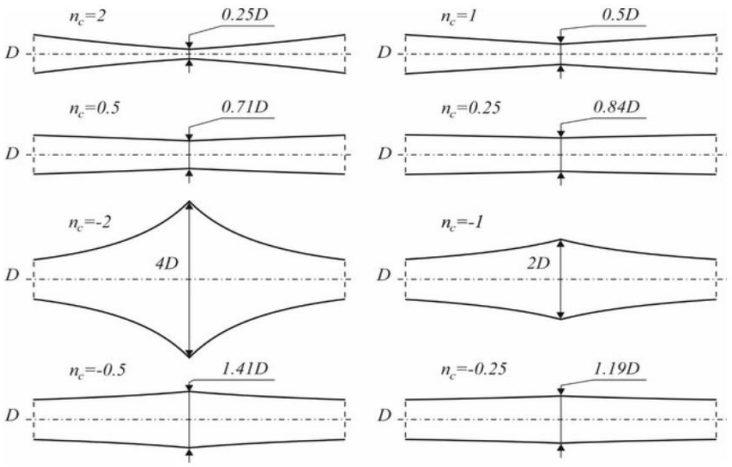
The concepts outlined in this section are summarized in Figure 1, which illustrates the influence of geometry and material architecture on capillarity across simple, natural, and engineered systems. In fig.1a, capillary tubes with varying contraction and expansion indices (ncn_cnc) demonstrate how channel shape alters meniscus curvature and suction pressure, extending Jurin's law beyond simple cylindrical pores. Fig.1b shows natural and synthetic fibrous porous networks, such as cellulosic paper, nonwovens, collagen, and hydrogels, where capillarity arises from interconnected pores between fibers; here, fiber diameter, density, and wettability control absorption and transport. Fig.1c presents engineered lattice wicks produced by additive manufacturing, highlighting how pore size, connectivity, and unit-cell geometry can be deliberately designed to balance capillary pressure and permeability. Together, the images capture the progression from fundamental single-pore physics to complex natural networks and finally to advanced engineered structures for controlled fluid management.

Classification of Capillary Materials. Capillary materials can be systematically classified based on their material origin (natural vs. synthetic), architectural form (fibrous, foam, lattice, composite), and pore scale (micro-, meso-, macro-, or hierarchical). Such classification helps to identify which classes are best suited for particular applications where capillarity drives liquid transport.

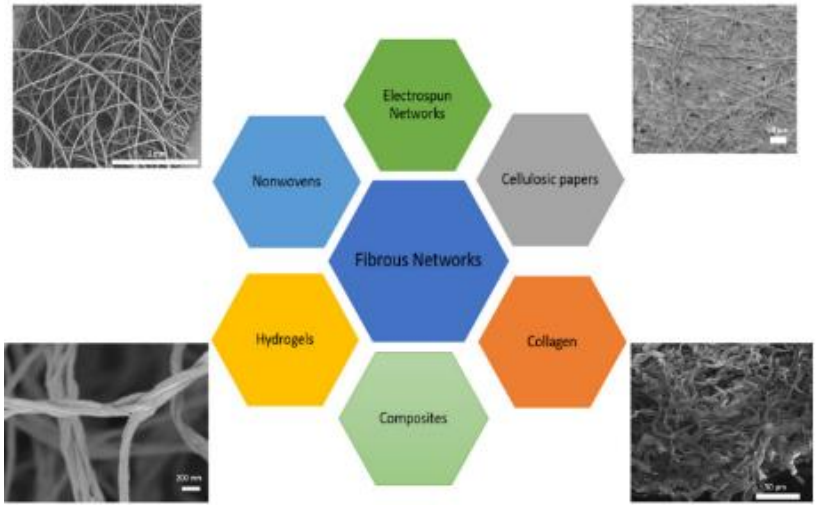
Natural vs. Synthetic Materials; Natural materials such as cellulosic papers, cotton fibers, and plant-derived foams exploit inherent fibrous or porous structures to generate capillarity. They are widely used in low-cost wicking applications (e.g., paper-based microfluidics, absorbent textiles) but often lack tunability and long-term stability [19]. Synthetic materials-including ceramics, metals, polymers, and composites-are engineered to optimize pore size, shape, wettability, and connectivity. They provide higher durability, controlled properties, and suitability for demanding applications such as heat pipes, biomedical scaffolds, and building insulation [20].

Porous Architectures; Fibrous Networks Natural and synthetic fibrous mats (papers, electrospun fibers, collagen scaffolds) exhibit fast capillary rise due to small fiber spacing and large surface area. They are important in textiles, diagnostics, and biomedical applications but can suffer from irregular pore distribution and mechanical weakness[13].

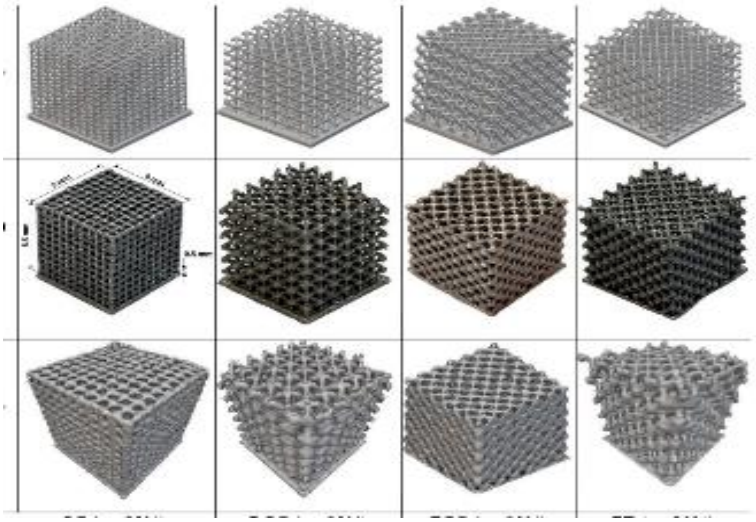
Foams; Porous foams (metallic, ceramic, or polymeric) consist of interconnected open pores with high porosity. They offer good permeability and storage capacity but usually have relatively large pore sizes, limiting capillary pressure [21]. Lattices and Periodic Cellular Structures Additively manufactured lattice wicks (SC, BCC, FCC, FT) enable precise control of pore geometry, connectivity, and periodicity. These structures are particularly promising for thermal management and high-performance devices where predictable flow and mechanical strength are required [22]. Ceramics and Composite Ceramics Ceramics offer high capillary pressure due to fine pores, combined with thermal and chemical stability. Composite ceramics and hybrid metal–ceramic systems allow hierarchical porosity, enabling a balance between suction and permeability [23].



(a) capillary tubes of varying geometry demonstrate the dependence of liquid rise on pore radius and channel shape



(b) fibrous porous networks illustrate capillarity in natural and polymeric systems



(c) engineered lattice wicks fabricated via additive manufacturing show how pore geometry can be precisely designed for enhanced fluid management

FIGURE 1. Conceptual illustration of capillarity across scales and materials

Polymers and Hydrogels Porous polymers and hydrogels provide lightweight, flexible, and biocompatible options. Their tunable swelling and wettability make them attractive for microfluidics, biomedical devices, and wound dressings, although their thermal stability and mechanical strength are limited [24] .

Pore Scale and Hierarchical Porosity Porous materials are commonly classified into micropores (< 2 nm), mesopores (2–50 nm), and macropores (> 50 nm) according to IUPAC guidelines [25]. For capillary-driven transport, pores in the micrometer-to-millimeter range are especially relevant, since they can sustain both capillary suction and flow. Hierarchical systems-combining small pores (for strong suction) with large pores (for permeability)-are particularly effective, as demonstrated in hybrid ceramic–metal structures [23].

Comparative Overview

- Fibrous networks: rapid uptake, low cost, but mechanically weak.
- Foams: good permeability, large pores, but limited capillary pressure.
- Lattices: precise, predictable, and mechanically robust, but costly to fabricate.
- Ceramics: excellent capillarity and durability, but brittle and complex to manufacture.
- Polymers/Hydrogels: flexible and biocompatible, but limited thermal/mechanical stability.

Figure 2 presents a hierarchical classification of capillary materials into three broad categories: natural, engineered, and advanced materials. Natural materials include fibrous structures such as cotton, wood, and silk, and other porous systems like sponges or rocks. Engineered materials encompass polymers, ceramics and composites, metals and alloys, and hybrid categories, each of which can be designed as fibrous networks, foams, lattices, or layered composites. Advanced materials represent the frontier of capillarity design, including biomaterials (e.g., artificial tissues, biodegradable scaffolds), nano-engineered systems (e.g., graphene aerogels, nanoporous frameworks), and smart or stimuli-responsive materials that adapt their capillarity dynamically. This classification illustrates the diversity of available capillary materials and highlights how structural form-fibrous, foam, lattice, or composite-recurs across multiple material classes.

Application-Driven Design of Capillary Materials; In this section, we examine how different applications impose specific demands on capillary material design. We illustrate how performance requirements (capillary pressure, permeability, wettability, mechanical robustness, etc.) shape the choice or engineering of material architectures. Key application domains include thermal devices, diagnostics & microfluidics, environmental sensors, and fluid flow roles in construction or building materials.

Thermal Management (Heat Pipes, Evaporative Cooling, Vapor Chambers)

- In thermal devices like heat pipes and vapor chambers, high heat flux demands mean that the wick's capillary pressure must be high enough to return working fluid against gravity and sustain thin-film evaporation, while also maintaining >= permeability for fluid replenishment. The filling coefficient (how well the porous structure fills with liquid) drops when permeability is too low, hurting performance. For example, Li (2021) showed that wicks with larger permeability but smaller pore sizes can have lower filling coefficients but better overall capillary performance under some thermal loads [26].
- Seo et al. [27] investigated mesh-structured wicks, measuring porosity, permeability, and effective pore radius, and how these relate to capillary limit (the maximal heat load before dry-out).
- The gradient pore size strategy is particularly useful: in one study, wicks whose pore size changes along the thickness (from coarse to fine) help balance the trade-offs: coarse pores for fast fluid supply; fine pores for high capillary pressure.

Diagnostics & Microfluidics; Paper-based microfluidic/capillary flow devices use natural fibrous materials (paper, nitrocellulose) or synthetic hydrophilic channels. Key design considerations include wettability, channel or pore dimension (to control flow rate), and detection signal timing. Aryal et al. [28] demonstrated a paper device for detection of heavy metals which delivers a colorimetric response in ~8 seconds using capillary flow in paper.

- Materials used in flowing or wetted environmental conditions must be stable, maintain wettability, resist fouling, and yet have sufficient capillary supply. The pore microstructure evolution study by. Zheng et al. [29] shows how sintering temperature changes pore structure and thereby capillary behavior in ceramic foams or porous metals.

RESEARCH RESULTS

The examples above demonstrate that capillary material design is highly application-specific, with each domain requiring a balance between capillary pressure, permeability, wettability, and structural stability. To consolidate these findings, Table 1 summarizes representative case studies across thermal management, microfluidics, and porous

ceramics. The table highlights the interplay between material choice, pore characteristics, and functional performance, providing a comparative framework for selecting or engineering capillary materials in different contexts.

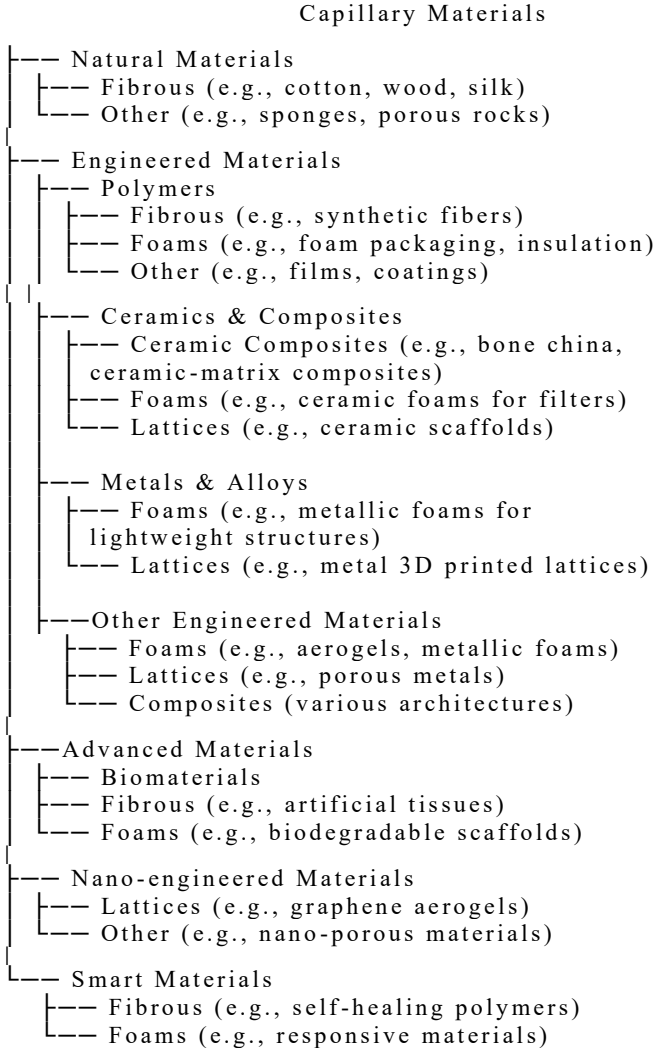


FIGURE 2. hierarchical classification of capillary materials

Strategies for Overcoming Capillary Trade-offs. As seen in previous sections, capillary materials often face competing design requirements: small pores produce stronger capillary pressure but lower permeability, while large pores improve fluid transport but reduce suction. To overcome these trade-offs, researchers have devised several strategies centered around architectural and compositional design. Below we present key strategies supported by recent literature.

Bilayer and Multilayer Wicks. Bilayer ceramic wicks - Boubaker et al. [33] demonstrate that using a bilayer structure (fine-pored layer plus coarse secondary layer) significantly enhances evaporator performance by reducing casing temperature and increasing critical heat flux compared to homogeneous wicks.

• Bimodal conductivity–pore design Mottel et al. [34] propose a wick architecture where the inlet layer (small pores, low thermal conductivity) serves as a capillary lock and reduces parasitic heat conduction, while the second, high-conductivity layer with larger pores supports fluid transport and heat spreading. This design notably increases permissible heat loads.

Gradient Porosity via Freeze-Casting. Freeze-cast gradient Ni wicks - Lloreda-Jurado et al. [35] manufacture gradient-porosity nickel wicks via a directional solidification process. By controlling the freezing front and dispersant chemistry, a continuous gradient in pore size and morphology emerges, enhancing capillarity performance and addressing the pressure–permeability trade-off.

Hierarchical Porous Structures

Bijel-templated hierarchical materials - Lee et al. create hierarchically porous copper materials with both meso- and macropores using bicontinuous interfacially jammed emulsion gels. These structures combine strong capillary suction (from mesopores) with enhanced bulk flow capacity [36].

Directional and Asymmetric Transport. Structural heterogeneity for directional flow - Huang et al design porous media engineered to have directional or asymmetric liquid transport by embedding structural heterogeneity (e.g., pore size variations). This enables controlled capillary flow pathways, improving efficiency in applications like heatpipes or moisture wicking [37].

Vertically penetrative polymer membranes - Yang et al. review polymeric porous membranes designed with vertically aligned channels. These structures enhance water pumping effectiveness and mitigate issues like salt accumulation in evaporation and desalination systems [38].

TABLE 1. Application-driven case studies of capillary materials, showing how material structure, pore characteristics, and design strategies determine functional performance.

Application	Material / Structure	Pore Characteristics	Performance Findings	Reference
Heat pipes / Vapor chambers	Sintered wick structures	Controlled pore size (tens of µm), ~50–70% porosity	Small pores → high capillary pressure but low permeability; trade-off impacts filling coefficient.	Li, 2021[26]
Heat pipes (mesh wick)	Stainless-steel mesh wick	Porosity ~0.55; pore radius ~10–50 µm	Permeability strongly influences maximum capillary limit (heat transport capacity).	Seo et al., 2022 [27]
Loop heat pipe wick	Gradient pore-size wick (coarse → fine)	Large pores (supply) + small pores (suction)	Combines high permeability and strong suction; increases maximum heat load.	Lu et al., 2022 [30]
Heat pipe modeling	Capillary wick (ceramic, metal, polymer)	Effective pore radius as main design input	Modeling shows small pores maximize capillary pumping; large pores minimize flow resistance → hybrid designs optimal.	Caruana et al., 2025 [31]
Microfluidic diagnostics	Paper-based channels (cellulose, nitrocellulose)	Fiber gaps ~10–50 µm	Enables colorimetric heavy metal detection in ~8 s; flow driven solely by capillarity.	Aryal et al., 2023 [28]
Capillary microfluidics (general)	Capillary pumps, valves, porous channels	Microchannels and porous pads; hydrophilic surfaces	Flow rate and reproducibility depend on geometry and surface treatment.	Khanjani et al., 2025
3D-printed bioanalytical devices	Printed porous microchannels	Tunable by CAD design; surface can be hydrophilic-coated	Additive manufacturing allows precise flow control, mixing, and integration into lab-on-chip devices.	Azizian et al., 2023 [32]
Porous ceramics for fluid absorption	Ceramic foams (sintered)	Porosity 0.3–0.8; pore diameter 10–200 µm	Heat treatment alters pore structure; balance between absorption and permeability.	Zheng et al., 2022

Patterned Surface Wettability. Wettability gradients - ACS Chemical Reviews covers strategies for patterning wettability on surfaces to guide and control open-surface capillary transport via smooth gradients or abrupt steps in surface energy. These techniques help in spreading or directional flow in applications such as microfluidics and evaporative cooling [39].

Design Rules and Trade-offs. In capillary materials design, one of the most persistent challenges is balancing capillary pressure (which increases with smaller pores) against permeability (which decreases with smaller pores). Navigating this trade-off requires systematic strategies and quantitative frameworks. This section presents design rules, scaling insights, and modeling approaches that help guide optimal design choices.

Fundamental Trade-Off Between Capillary Pressure and Permeability

Inverse relationship: Across many porous materials, capillary pressure (Pc) inversely correlates with characteristic pore size, while permeability (k) grows with larger pores or higher porosity. The Pore Microstructure Evolution study by Zheng et al [40] explicitly confirms that smaller pore sizes increase capillary pressure but reduce permeability.

Bi-porous structures reduce trade-off: In porous aluminum wicks, Shen et al [41] demonstrate that bi-modal pore size distributions (a mix of small and large pores) can improve capillary pressure while maintaining or even improving permeability under a fixed overall porosity (~70%).

Models and Scaling Laws

• Kozeny–Carman equation provides a classical relationship between permeability k, porosity ε, pore size dp, and tortuosity:

$$k = \frac{\varepsilon^3 \, d_p^2}{c(1-\varepsilon)^2 \tau^2} \tag{2}$$

This equation shows that permeability scales with the *square of pore size* multiplied by porosity terms [15].

Capillary pressure–saturation scaling: Lan et al [42] propose a scaling method for capillary pressure curves under various wetting conditions, which could help normalize performance across material classes.

Composite or graded wicks: Caruana et al. [15] highlight that creating graded pore size structures allows designers to achieve more effective compromises between capillary pressure and permeability than uniform porosity wicks.

Experimental Verification of Trade-off Principles

Permeability-porosity scaling: Hariti et al [43] derive a model showing how permeability scales with porosity, tortuosity, and pore distribution, giving designers quantifiable guidance.

Wick porosity effects: De Kerpel et al [44] show experimentally that selecting a wick involves a trade-off-materials with higher permeability often have lower capillary pumping power, and vice versa.

Mesh wick optimization: Shattique et al. [45] investigate single-layer metal mesh wicks, demonstrating how mesh geometry can be tuned to enhance resistance to capillary pressure drop while maintaining high intrinsic permeability.

Design Rules. From these studies, we can extract actionable design rules:

1. Use bi-modal or graded pore architectures to combine small pores (for capillary suction) with large pores (for fluid transport).
2. Apply Kozeny–Carman or similar scaling laws to estimate permeability based on porosity and pore size; useful in early-stage material selection.
3. Employ modeling of capillary pressure–saturation relationships (e.g., via Leverett J-function or pressure curves) to predict wetting behavior in materials with varying pore structures.
4. Optimize mesh parameters or strut geometries where metal or lattice wicks are used, to retain permeability while avoiding dry-out.
5. Consider dimensionless numbers such as the capillary number (ratio of viscous to capillary forces) and other scaling groups to understand dynamic vs. static transport regimes.
6. Experimentally quantify filling coefficient and capillary rise velocity, since these metrics integrate both capillary pressure and permeability effects.

Outlook and Future Directions. As research into capillary materials advances, emergent themes point toward designing adaptive, multifunctional, and smart systems that surpass traditional passive wicking capabilities. These innovations promise to expand the utility of capillarity for applications in energy, building materials, environmental control, and responsive devices.

Capillary-Active Building Materials. Building envelopes increasingly target combined requirements of thermal insulation and moisture management. Capillary-active insulation materials, such as those reviewed by Yıldız and Tanacan [46], allow wall assemblies to absorb and redistribute moisture via capillarity, thus offering indoor humidity regulation, mold prevention, and energy efficiency.

Relatedly, bacterial cellulose aerogel films present thin, sustainable, highly porous films with low thermal conductivity (as low as 13 mW/(K·m)), demonstrating possible applications in retrofit thermal insulation combined with wicking behavior.

Smart and Adaptive Capillary Materials

The frontier of capillary material science increasingly involves smart soft materials with dynamic structure and functions. Zeng et al [47] review these systems-characterized by multiscale architecture and dynamic responsiveness-that can adapt their porosity, wettability, or shape under external stimuli (temperature, moisture, mechanical stress).

Similarly, programmable nanocellulose-based hydrogels with embodied logic Arsuffi et al can perform logical functions (AND, OR, NOT) and change swelling/bending behavior according to multiple stimuli (pH, temperature, light). These materials hint at decision-making capillary systems-that is, materials whose fluid uptake behavior can be dynamically controlled

Responsive and Interactive Materials

Walther et al [46-47] describe the shift from responsive materials (simple stimulus–response behavior) to truly adaptive and interactive systems. In the context of capillarity, this suggests future materials could actively regulate capillary uptake or release based on environment changes, or communicate fluid status for sensing/feedback loops.

Integrating Multifunctionality

Across energy, environmental, and biomedical domains, the trend is toward integrating capillary transport with additional functions such as thermal storage, moisture regulation, sensing, and responsiveness. The future of capillary material engineering lies in this multifunctional integration-materials that not only move fluids but adapt, communicate, and enhance system performance.

CONCLUSION

This review demonstrates that capillarity is not only a natural phenomenon but an engineering principle that can be designed, optimized, and applied across scales and material classes. Recognizing it as such allows capillary action to be positioned alongside conductivity, strength, or toughness as a fundamental design parameter in materials science.

A key lesson is that the apparent trade-off between capillary pressure and permeability is not a hard limit, but a design challenge. Through bilayer, gradient, and hierarchical architectures, materials can simultaneously achieve strong suction and high flow capacity, overturning a long-standing assumption in porous media science.

The rise of adaptive and multifunctional systems points to a broader shift: future capillary materials will not only transport fluids but also regulate, sense, and respond to their environment. In doing so, they will enable new generations of technologies, from heat management devices and biomedical platforms to capillary-active building materials for sustainable architecture.

Taken together, these insights suggest a new perspective: engineering capillarity offers a unifying paradigm for fluid management across disciplines, one that connects physics, biology, materials design, and sustainability. By framing capillary action as a strategic design tool, researchers can create multifunctional materials that address urgent challenges in energy, health, and the built environment.

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