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## Introduction

As modern technology advances, the demand for advanced functional materials continues to grow. However, most functional materials have significant drawbacks, such as high costs and complex manufacturing processes, which make it challenging to meet the increasing demands of the application market. In this context, paper-based functional materials have emerged as a key focus of cutting-edge technology development. Compared to traditional functional materials, paper-based functional materials offer several advantages, including strong functional properties, a wide range of applications, ease of production, low cost, biodegradability, and recyclability. These benefits make paper-based functional materials a preferred choice for future technological development.



### 1.1 Definition of Paper-based Functional Materials

Paper-based functional materials are advanced composite materials made primarily from plant fibers. By incorporating various functional materials—such as inorganic mineral fibers and high-performance fibers (e.g., aramid fibers, carbon fibers, and polyimide fibers)—and using modern papermaking techniques, these materials form a three-dimensional network structure with specific properties and high added value [1]. As a key component in the production of specialty paper and paperboard, the functional characteristics of these materials depend significantly on the high-performance fibers or inorganic mineral fibers added during their manufacture [2].

In paper-based functional materials, the paper serves as the substrate, with various functional materials loaded onto it [3]. These functional materials mainly include modified natural polymers like starch and fibers, synthetic organic polymers, and inorganic mineral materials, collectively known as papermaking chemicals. For many years, papermaking chemicals have been recognized as new functional materials and are included in the national catalog of industries, products, and technologies encouraged for development. Papermaking chemicals have two primary applications [4]. First, the chemicals include high-performance starch derivatives, water-soluble polymers, and newly developed nanocellulose that are used for the enhancement of ordinary paper (or paperboard). They are used to improve paper



strength (dry strength, wet strength, and surface strength), retention, and filtration; reduce fiber and filler loss; and mitigate wastewater pollution. They also enhance paper properties like whiteness, smoothness, printability, softness, stiffness, tear resistance, water resistance, and breathability. Second, papermaking chemicals are applied in the production of specialty paper, which is designed for specific functions such as hydrophobicity/oleophobicity, hydrophilicity/oleophilicity, filtration/separation, flame retardancy, insulation, conductivity, luminescence, high barrier properties, detection and separation, construction and home decoration, fruit and vegetable preservation, electromagnetic shielding, dust and static resistance, corrosion and rust resistance, and antimicrobial and insect resistance. These papers have unique properties and are used in various specialized applications.

## 1.2 Raw Materials of Paper-based Functional Materials

The various functional materials incorporated into or composited with paper-based substrates can be categorized based on their raw material types into natural polymer materials, inorganic mineral materials, and organic polymer materials (Table 1.1).

**Table 1.1** Major raw material composition of functional materials incorporated into (or composited with) paper-based substrates.

Classification	Raw materials	Functional products	Main raw material sources
Natural polymers	Starch	Starch-based biological products	Corn, potatoes, cassava, etc.
	Plant fibers	Nanofibers, cellulose-based biological products	Wood, bamboo, rattan, cotton, etc.
Inorganic minerals	Inorganic minerals	Functional materials such as conductive, magnetic, flame-retardant, reinforced, thermal insulation, wear-resistant, insulating, air purification, and barrier materials	Inorganic minerals, carbon-based materials, magnetic materials, rare earth materials, metallic materials, etc.
Petroleum-based organic polymers		Functional polymer materials, such as strengthening agents, retention aids, filtration aids, adhesives, defoamers, corrosion inhibitors, oil-resistant agents, water-resistant agents, softening agents, dispersants, and deinking agents	Petrochemical raw materials
		High-performance synthetic fibers	Aramid fibers, polyacrylonitrile fibers, polyester fibers, nylon fibers, vinylon, polypropylene fibers, etc.

### 1.2.1 Natural Polymers

Key raw materials include starch and cellulose, which are abundant renewable resources with strong compatibility with papermaking fibers and full biodegradability. Modified starches, produced through physical, chemical, or biological modifications, are essential in papermaking for enhancing strength, retention, filtration, surface sizing, coating adhesion, and interlayer bonding.

Starch-based functional materials are derived from natural starch that has been modified through physical, chemical, or biological methods to impart various functional properties. This kind of starch is commonly referred to as “modified starch.” In the papermaking industry, modified starches include enzyme-converted starch, anionic starch (such as oxidized starch, phosphate starch, and carboxymethyl starch), cationic starch, amphoteric and multifunctional modified starch, cross-linked starch, hydroxyalkyl starch, composite modified starch, and grafted starch.

The benefits of these modified starches include low gelatinization temperature, good transparency and stability of the starch paste, strong affinity with fibers, excellent film-forming properties, and resistance to acids and alkalis. Modified starches are suitable for almost all types of paper and paperboard, typically used at a dosage of around 1%. They serve various functions such as strengthening, retention aid, filtration aid, surface sizing, coating adhesion, and interlayer bonding. These properties make modified starches indispensable in the papermaking industry [5], earning them the nickname “industrial MSG.”

Nanocellulose consists of cellulose fibers with a one-dimensional size less than 100 nm, exhibiting unique properties characteristic of nanomaterials. These properties include size effects, quantum effects, surface effects, and macroscopic quantum tunneling effects, making their physical, chemical, and mechanical characteristics significantly different from those of macroscopic materials. As a promising new material for the “post-carbon fiber era,” nanocellulose has the potential to replace metals and plastics in the future.

Nanocellulose is produced through chemical, physical, and biological methods, and its development and industrialization are still in the early stages globally. Nanocellulose and its modified products offer exceptional properties such as high strength, oil resistance, water resistance, and barrier functions, making them highly promising as biomass-based functional materials in the papermaking industry. Additionally, cellulose derivatives like carboxymethyl cellulose and hydroxypropyl cellulose are also important in papermaking coatings, contributing to improved paper properties [6].

Plant-based specialty long fibers primarily include bast fibers (such as hemp, mulberry bark, paper mulberry, and jute) and cotton fibers. Specialty papers made from these plant-based long fibers through papermaking processes exhibit high breathability and high strength, making them widely used as filtration materials for gases and liquids.

### 1.2.2 Inorganic Minerals

Common materials include talc, kaolin, and bentonite, which are used to enhance paper whiteness, smoothness, retention, and filtration. Other inorganic materials like mineral wool, expanded perlite, aerogel blankets, and foam glass serve as thermal insulators. Metal-based materials are often used for heat insulation, while flame retardants typically include inorganic phosphates, borates, metal hydroxides, oxides, and salts. Carbon-based materials, magnetic materials, rare earth materials, and metals also play significant roles in various functional papers.

### 1.2.3 Petroleum-based Organic Polymers

Derived from petrochemicals, these materials include superhydrophobic and superoleophobic functional papers used for self-cleaning, corrosion resistance, and oil transport. Common thermal insulation materials include expanded polystyrene, polyurethane sponge, cork, phenolic foam, and cellulose. These materials are typically processed through papermaking technologies to meet high-temperature and insulation requirements. Flame-retardant materials often involve halogen, phosphorus, and nitrogen compounds, and noncombustible fibers.

Paper-based functional materials derived from petrochemical raw materials come in various forms. For example, durable super-oleophobic and hydrophobic paper-based functional materials are primarily created by combining perfluoroalkanes and block copolymers with functional end groups (fluorinated monomers) through coating or similar methods. These super-repellent materials, which are both oleophobic and hydrophobic, are widely used in applications such as self-cleaning, corrosion resistance, oil transportation, antibiofouling devices, oil collection, antifouling, microdroplet transfer, and oil-water separation.

Common organic polymer thermal insulation materials include expanded polystyrene, polyurethane sponge, cork, phenolic foam, and cellulose. These materials are typically made using fibers as the main raw material and formed through papermaking techniques. They differ significantly in structure and properties from traditional paper-based materials and are often used in high-temperature fields such as aerospace and as outer protective layers for various insulation materials.

Organic polymer flame-retardant materials mainly include halogenated, phosphorus-based, and nitrogen-based compounds. Additionally, flame-resistant or noncombustible fibers can be used as raw materials in paper making processes to produce flame-retardant papers. These materials are widely used in construction, packaging, interior decoration, automotive filtration, cable wrapping, etc.

High-performance fiber paper-based functional materials are made from natural plant fibers mixed with specialty fibers (including inorganic and synthetic fibers). Through dispersion, formation, and enhancement techniques, these materials are processed to meet specific performance requirements, resulting in a range of paper-based functional materials with both structural and functional properties.

Typical high-performance synthetic fibers used include aromatic polyamide fibers (poly (p-phenylene terephthalamide)), ultra-high-molecular-weight polyethylene fibers, and polyimide fibers. These high-performance fiber paper-based materials are widely used in personal protection, bulletproof armor, rubber products, asbestos substitutes, automotive friction materials, high-grade insulation paper, and paper-based honeycomb structures and are essential in advanced fields such as aerospace, national defense, electronic communication, petrochemicals, and marine development.

### 1.3 Properties and Applications of Paper-based Functional Materials

Paper-based functional materials have a structure and properties that are completely different from traditional paper. They primarily exhibit mechanical properties; thermal characteristics; electrical, electronic, and magnetic properties; optical characteristics; other physical properties (such as adhesion, separation and filtration, water, oil, and gas adsorption properties); chemical properties; and biochemical properties. These materials overcome the limitations of single natural plant fiber materials, which cannot withstand harsh conditions such as high impact, high temperature, high humidity, and high corrosion. Paper-based functional materials are widely used in important fields such as industry, agriculture, aerospace, electronic information, healthcare, food safety, and transportation.

Starch-based functional materials are the most widely used biomass-based products in the papermaking industry, with the broadest range of applications and the most comprehensive functional roles. They have been widely adopted in China, with an annual consumption of over a million tons in the papermaking industry. These materials play an irreplaceable role in improving quality and performance, saving energy and reducing emissions, conserving wood resources, and protecting the ecological environment [7].

High-performance fiber paper-based functional materials possess excellent properties such as low density, high specific strength, high specific stiffness, and high-temperature resistance. They are strategic functional materials with significant applications in fields such as rail transportation, aerospace, and national defense technology. The preparation technology for these materials is internationally recognized as a challenging issue and has been tightly restricted by developed countries. There are several scientific problems and technological bottlenecks in key areas such as fiber preparation and dispersion, fluid delivery and forming, and hot pressing and reinforcement, which severely restrict the development of advanced domestic functional materials, such as insulation and structural weight reduction, required for high-speed trains and aircraft manufacturing.

Nanocellulose is lightweight, biodegradable, and derived from a wide range of sources. It has excellent properties, including high strength, high specific surface area, high polymerization degree, high crystallinity, and low thermal expansion coefficient. Compared to other nanomaterials, nanocellulose has advantages such as

good biocompatibility, biodegradability, and renewability. More importantly, the surface of nanocellulose contains abundant hydroxyl groups, making it highly reactive. By introducing functional groups, the functionality of nanocellulose materials can be tailored, making them more adaptable to various application fields with different needs. Nanocellulose can be widely used in applications such as paper and paper-board reinforcement, barrier properties, anti-oil, waterproof materials, resin composites, lightweight high-strength automotive parts, fully degradable high-strength materials, filtration and separation materials, green degradable barrier packaging materials, and personal care materials. It is expected to elevate the traditional papermaking industry to a fully biodegradable functional materials industry.

The close integration of other organic polymers, inorganic materials, and metals with papermaking has made significant contributions to technological advancements in China's specialty paper sector, with huge development potential. For example, by adding specialty chemicals with hydrophobic, oleophobic, hydrophilic, or oleophilic properties, and using physical-chemical methods, chemical methods, surface coating, and nanoparticle deposition techniques, paper or fibers can be modified to create hydrophobic/oleophobic/hydrophilic/oleophilic paper-based functional materials. Through flame-retardant treatment, such as adding flame retardants during the papermaking process, the resulting flame-retardant paper-based materials exhibit noncombustibility and high-temperature resistance [8]. These materials are widely used in fields such as construction, packaging, interior decoration, automotive filtration, and cable insulation. They can also be used for the long-term safe preservation of books and important documents (e.g., archives and certificates). Thermal-insulation paper-based functional materials, primarily made from fibers, are characterized by thermal insulation performance, lightweight, loose, porous structure, and low thermal conductivity. Other typical paper-based functional materials, such as paper-based analytical detection chips, paper-based ceramic carriers, paper-based flexible electronic circuits, paper-based light-emitting and heating materials, and paper-based friction materials, also have vast application prospects across multiple sectors of the national economy.

#### 1.4 Economic and Social Value of Paper-based Functional Materials

Paper-based functional materials represent an advanced new field of materials, expanding the application scope of functional materials while playing an increasingly important role in the technological advancement of papermaking and related industries. These materials have immense economic and social values, with far-reaching significance, particularly in the areas of specialty paper and papermaking chemicals.

On the one hand, papermaking chemicals can impart various special superior properties to paper, significantly improving paper quality, enhancing paper machine efficiency, promoting the development of new and more valuable paper varieties, and effectively conserving valuable papermaking resources (including wood,

water, energy, etc.). They also substantially reduce environmental pollution in the papermaking process and have strong relevance in promoting the development of downstream industries such as news, publishing, printing, packaging, electronics, automotive, food, and tobacco. With the development of China's national economy, the papermaking industry is progressing toward larger and faster paper machines, neutral papermaking processes, and closed-loop whitewater recycling. However, it faces significant bottlenecks in resources, environment, and technology. Papermaking chemicals are key materials for overcoming these bottlenecks, playing an increasingly crucial role in improving quality, transforming, and upgrading the papermaking industry, saving energy, reducing emissions, conserving resources, and developing and applying high-grade and specialty papers. For example, a national science and technology project undertaken by Xianping Yao's research team developed a series of new products using starch as the main raw material and multistage modification technology, which have been widely adopted in China's papermaking industry. These products have been proven to increase paper strength by 15% to 25%, save 10% to 35% of pulp, reduce energy consumption by 5% to 15%, improve the retention rate of fine fibers and fillers by 10% to 40%, and decrease white water concentration by 20% to 30%.

On the other hand, specialty paper differs from traditional paper and paperboard in structure and performance, offering flexible design options for properties such as optical, electrical, magnetic, thermal, and acoustic characteristics. It is widely used in various fields that are closely related to people's lives, such as cultural industries, manufacturing, agriculture, and healthcare, and has important applications in national defense, aerospace, and rail transportation. Specialty paper is one of the country's important strategic materials, and its importance and value are self-evident. In terms of economic value, specialty paper is energy efficient, environmentally friendly, high profit, and rapidly developing. Although the demand for single products may not be large, the variety of products and their high economic value make them very significant. For instance, key technologies for enhancing paper-based functional materials using specialty fibers have led to the development of high-performance products such as nanoquantitative filter paper, nanoautomotive filters, flame-retardant steel paper, and waterproof insulating steel paper. In just a few years, production and sales have reached 35,000 tons, generating an output value of 700 million RMB and tax revenue of 70 million RMB.

Nanocellulose, prepared primarily from plant fibers used in papermaking, is a cutting-edge biomass material that not only exhibits the properties of nanomaterials but also has features such as lightweight, high strength, biodegradability, good biocompatibility, high thermal stability, and strong hydrophilicity. Its density is only one-fifth that of stainless steel, while its strength is more than five times greater, making it regarded as a new material for the "post-carbon fiber era." Nanocellulose has the potential to replace metals and plastics and is a global research hotspot. According to the USDA Forest Service, the global market potential is estimated at 35 million tons. It can be widely used in ordinary paper, specialty paper, fully degradable biomass materials, and health-related fields, and its lightweight and high-strength properties make it suitable for aerospace, rail transportation, and other major

engineering sectors. The current international market price of nanocellulose is over 1 million RMB per ton, demonstrating its immense economic and social values. Countries around the world are paying close attention to its development, and its progress is rapid. However, the industry is still in the early stages of commercialization, facing issues such as immature technology, small scale, and high prices. China has listed nanocellulose as a key research project in the 13th Five-Year Plan and, in collaboration with the South China University of Technology, Hangzhou Mechanical and Electrical Design Institute, and other institutions, has established the country's first pilot-scale demonstration line for the green preparation of nanocellulose at the Hangzhou Chemical Research Institute. A series of high-value application studies have been conducted, and the commercialization and high-value applications of these results are expected, with promising prospects ahead.

## 1.5 Development Trends of Paper-based Functional Materials

The future development trends in the field of paper-based functional materials will primarily focus on two aspects: new processing technologies and new products. A brief introduction to the development of these two aspects is provided below.

### 1.5.1 Development of New Technologies

#### 1) Foam forming technology

Foam forming is a papermaking technology developed in the 1970s that allows the production of nonwoven materials with good uniformity, high bulk density, and high porosity on paper machines. Compared to current slow-flow web formation or wet-laid nonwoven fabric production platforms, the successful application of foam forming technology in commercial production enables paper machines to produce nonwoven substitutes at a lower cost. After a series of modern technological improvements, the new foam-forming system has been applied to the commercial production of specialty paper.

#### 2) Stretchable paper technology

Stretchable paper technology, developed by Finland's VTT company, primarily relies on mechanical processing to achieve 20% and 16% elongation in the longitudinal and lateral directions, respectively. Stretchable paper is a novel concept designed to replace plastic with natural paper, making it more sustainable, especially for single-use packaging. This paper can be supplied in rolls and processed on traditional lines used for polymers, including printing, coating, and other processes. Potential application areas include pallet packaging, medical packaging, paper cups and other liquid containers, and furniture decoration.

### 1.5.2 Development of New Products

#### 1) Carbon-fiber-reinforced thermoplastic resin molding (paper-based thermoplastic resin composite material)

Developed by Japan's Awa Paper, this technology disperses carbon fibers (with a length of 3–6 mm) and thermoplastic resin fibers (such as polypropylene (PP) and polyethylene (PE)) in water, which are then processed into continuous fiber-reinforced thermoplastic composite (CFRTP) products through papermaking, lamination, and hot pressing. The strength of CFRTP is approximately five times that of general resins like PP and PE. Particularly, CFRTP made with polyamide fibers can achieve tensile strength equivalent to aluminum alloy "A5052" at the same volume ratio, but with only one-third to one-half of its weight.

2) Energy-storing paper

Developed by Swedish researchers, this paper, made of nanocellulose and conductive polymers, can store up to 1F of electrical energy in a sheet with a diameter of 15 cm and a thickness of just a few millimeters, similar to current supercapacitors on the market. This material can be charged and discharged hundreds of times, with each charging session taking just a few seconds. It can be used as a backup energy source during peak electricity demand and as a supercapacitor at electric vehicle charging stations.

3) New degradable paper mulch

Developed by Walki, a Finnish company, this new type of paper mulch uses kraft paper as the base material, coated with a degradable coating. The product provides excellent coverage, reduces weeds, and does not affect crop yields.

4) Porous titanium electrodes for water electrolysis

German scientists are attempting to use papermaking methods to create porous titanium electrodes for water electrolysis. The process involves adding a large amount of titanium powder during papermaking, resulting in paper with more than 75% titanium powder content. This paper is then sintered at high temperatures to remove organic components and sinter the metal powder into a porous electrode material. The thickness and pore structure can be adjusted by modifying the papermaking process. This electrode material provides an optimal, low-cost gas/liquid diffusion layer for polymer electrolyte membrane (PEM) electrolysis cells, ensuring uniform water distribution and smooth gas diffusion.

5) Polystyrene nanocomposite coatings to improve antibacterial properties of packaging paper

Polystyrene, titanium dioxide nanoparticles, and silver nanoparticles are used to prepare polystyrene nanocomposite coatings. When applied to packaging paper made from straw pulp (at 5% or 10% concentration), the coated paper exhibits improved breathability, tensile strength, water absorption, and barrier properties. The coating also shows strong antibacterial effects against *Pseudomonas aeruginosa*, *Staphylococcus aureus*, *Candida*, and other bacteria.

6) Sharklet-microstructure-coated release paper with breakthrough technology

A North American company has developed cast-coated release paper with a Sharklet microstructure. This innovation prevents bacterial growth on the paper surface without the use of toxic additives or chemicals.

## 7) Replacing single-use plastics with paper-based materials

Notably, the pollution caused by single-use plastics has become a serious threat to human health, and global efforts to combat plastic waste have gained widespread support. The papermaking industry, using plant fibers as the primary raw material, has abundant resources and the advantage of full biodegradability. With the successful development of high-strength, high-barrier nanocellulose, the use of paper to replace plastics, particularly single-use plastic products that take centuries to degrade, has seen significant breakthroughs. Once the technology matures, it is expected to drive a resurgence in the traditional papermaking industry.

In conclusion, the future development of paper-based functional materials offers vast potential. It is essential for material scientists and papermaking experts to work together to develop more advanced, high-performance, and widely applicable products to meet the growing market demand.

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