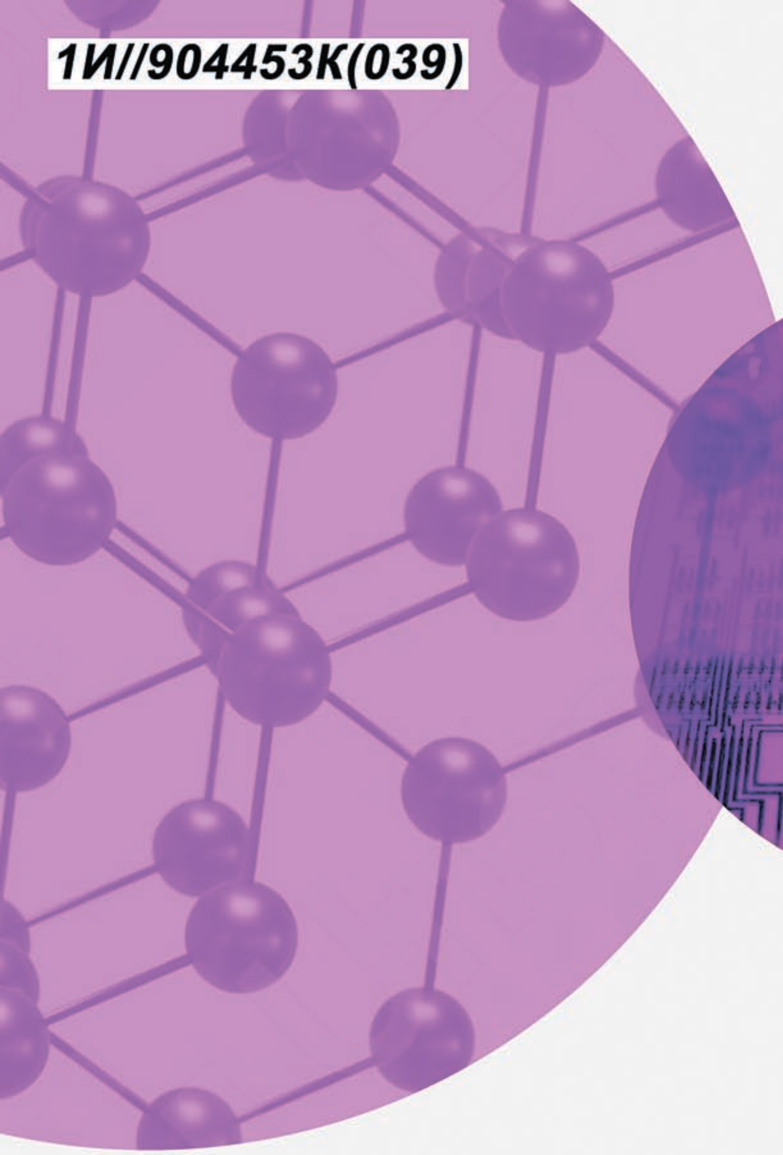

Patent
Landscape
Report

Graphite and its applications

WIPO

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Further information
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Key findings and insights

Named in 1789, the word graphite is derived from the Greek *graphein*, meaning "to draw or write." This stems from its primary use as the "lead" in pencils. From its humble beginning as a means of mark-making and writing, graphite came to prominence in the manufacturing of cannonball molds, because of its excellent refractory properties. Thereafter, graphite, owing to its combination of excellent electrical and thermal conductivity, and good chemical stability and corrosion resistance, became an indispensable material in various industrial applications. This WIPO Patent Landscape Report examines global graphite-related patenting activity in the last decade. The report uses information from individual country policies and market and business information to assess the current state of graphite technologies and identify innovation hot topics, as well as examining both better-studied areas and the emerging applications for graphite.

Innovation in graphite technologies has attracted growing interest in the last decade, but inventions have been concentrated in just a few geographical regions.

Globally, over 60,000 patent families in graphite technologies were filed from 2012 to 2021. Such a large volume of graphite-related inventions underscores the importance of the material across multiple industries.

Interest in graphite is global. Patents were filed by applicants from over 60 countries and regions. However, graphite-related patent families originated predominantly from just a few countries. China was the top contributor with more than 47,000 patent families, accounting for four in every five graphite patent families filed worldwide in the last decade. Among other leading countries were Japan, the Republic of Korea, the United States and the Russian Federation. Together, these top five countries of applicant origin accounted for 95 percent of global patenting output related to graphite.

Flake graphite and artificial graphite were the two preferred primary graphite sources.

Among the different graphite sources, flake graphite has the highest number of patent families, with more than 5,600 filed worldwide from 2012 to 2021. It has strong traction, particularly in China – the primary supplier of flake graphite to the global market. Supported by active research from its commercial entities and research institutions, China is the country most actively exploiting flake graphite and has contributed to 85 percent of global patent filings in this area.

At the same time, innovations exploring new synthesis methods and uses for artificial graphite are gaining interest worldwide, as countries seek to exploit the superior material qualities associated with this man-made substance and reduce reliance on the natural material. Patenting activity is strongly led by commercial entities, particularly world-renowned battery manufacturers and anode material suppliers, with patenting interest focused on battery anode applications.

Exfoliation techniques for bulk graphite processing are well-established.

The exfoliation process, which involves separating the carbon layers within graphite, has been extensively studied. Specifically, ultrasonic and thermal exfoliation have been the two most popular approaches worldwide, with 4,267 and 2,579 patent families, respectively. This is significantly more than for either the chemical or electrochemical alternatives.

Global patenting activity relating to ultrasonic exfoliation has decreased over the years, indicating that this low-cost technique has become well established. It is particularly popular among research institutions as an essential step in processing bulk graphite into graphite nanomaterials and graphene.

Thermal exfoliation is a more recent process. Compared to ultrasonic exfoliation, this fast and solvent-free thermal approach has attracted greater commercial interest.

Battery applications were a key driver, and will continue sustaining global graphite-related innovation.

As the most widespread anode material for lithium-ion batteries, graphite has drawn significant attention worldwide for use in battery applications. With over 8,000 patent families filed from 2012 to 2021, battery applications were a key driver of global graphite-related inventions. China has the most graphite patent families for battery applications, followed by Japan and the Republic of Korea. These top three regions have contributed to over 90 percent of patent families worldwide.

Innovations in this area are led by battery manufacturers or anode suppliers who have amassed sizable patent portfolios focused strongly on battery performance improvements based on graphite anode innovation. Besides industry players, academia and research institutions – Chinese universities, in particular – have been an essential source of innovation in graphite anode technologies.

The need for graphite in batteries is expected to increase further, owing to a rapidly growing demand for energy storage in support of the clean energy sector’s explosive market growth over recent years – particularly with respect to electric vehicles and large-scale energy storage. Increasingly, leading innovators are exploring graphite anodes for the next generation of battery technologies, as well as alternative anode solutions with a greater energy density and better performance.

Polymer and ceramic applications are graphite technology innovation hot topics.

Graphite for polymer applications was an innovation hot topic from 2012 to 2021, with over 8,000 patent families recorded worldwide. However, in recent years, in the top countries of applicant origin in this area, including China, Japan and the United States of America (US), patent filings have decreased. A large volume of patent applications followed by a downward trend suggests that it is a well-explored area with substantial technology accumulation. Overall, graphite inventions for polymer composites were strongly commercially driven, with four in every five related patent families having been filed by commercial entities.

Graphite for manufacturing ceramics represents another area of intensive research, with over 6,000 patent families registered in the last decade alone. Specifically, graphite for refractory is the key innovation focus worldwide. It accounted for over one-third of ceramics-related graphite patent families in China and about one-fifth in the rest of the world. Other important graphite applications include high-value ceramic materials such as carbides for specific industries, ranging from electrical and electronics, aerospace and precision engineering to military and nuclear applications.

Graphite applications for carbon brushes have reached saturation point.

Carbon brushes represent a long-explored graphite application area. That it is considered to be a well-established area is evident from related patenting activity worldwide.

There have been few inventions in this area over the last decade, with less than 300 patent families filed from 2012 to 2021. In addition, the majority of patent families originating from China – the top contributing country – were filed in earlier years. Furthermore, graphite for carbon brushes is gaining minimal traction from the rest of the world, with only sporadic patent filings having been made in the last decade. The overall number of patent families originating from the rest of the world filed between 2012 and 2021 is far lower than was filed between 1992–2001 and 2002–2011, respectively, indicating that carbon brush technology has entered the final stage of its technology cycle.

Graphite use for biomedical, sensor and conductive ink applications is emerging.

Biomedical, sensor, and conductive ink are emerging application areas for graphite that have attracted interest from both academia and commercial entities, including renowned universities and multinational corporations.

Typically for an emerging technology area, related patent families were filed by various organizations without any players dominating. As a result, the top applicants have a small number of inventions, unlike in well-explored areas, where they will have strong technology accumulation and large patent portfolios.

The innovation focus of these three emerging areas is highly scattered and can be diverse, even for a single applicant. However, recent inventions are seen to leverage the development of graphite nanomaterials, particularly graphite nanocomposites and graphene.

Introduction

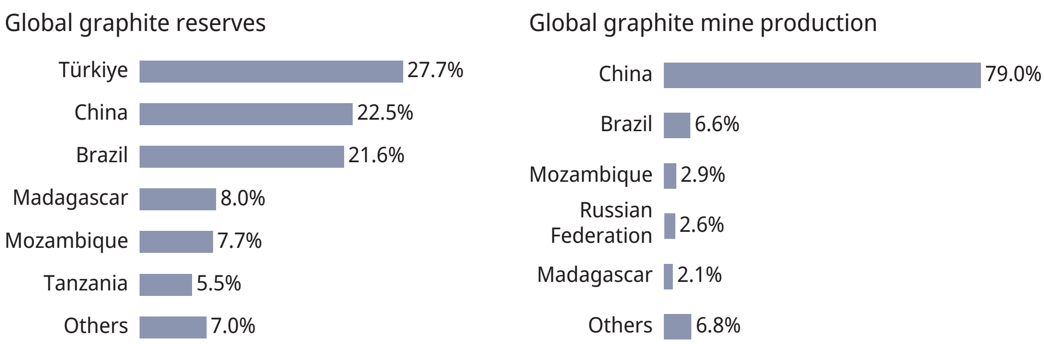
"Lead pencil" is a misnomer: pencils have never contained lead, but are instead made of graphite. Although the true composition of the so-called "lead" in pencils was identified and named graphite in the late 18th century (Uwaterloo, 2022), the term stuck.

The history of graphite dates back to the early 16th century, when an enormous deposit of pure, solid graphite was discovered in Borrowdale, England (Pencils, 2022). Locals used this coal-like mineral for marking sheepskin. When metallurgists encountered the substance, they mistook it for a type of black lead rather than a form of carbon, hence the origin of the term "lead pencil."

Graphite was named in 1789 from the Greek "graphein," meaning "to draw or write," stemming from its primary use in pencils (Uwaterloo, 2022). Graphite's first industrial application was not, however, for marking or writing. Rather, following its discovery, the English Government soon found it to be an excellent refractory material in the making of cannonball molds. The rounder and smoother cannonballs produced from such molds contributed to the English Navy's superiority at the time. Graphite use expanded in the 19th century to include in stove polish, lubricants, paints and foundry facings. But applications exploded in the 20th century, as production and purification methods improved.

However, although the industrial applications and demand for graphite are global, the natural material itself is found in only a few countries. According to the United States Geological Survey, Türkiye, China, Brazil, Madagascar and Mozambique are the top five countries with natural graphite deposits (USGS, 2012–2022). Together, they constitute around 80 percent of global graphite reserves (Figure 1). China is the biggest producer of natural graphite. In 2020, that country produced about 80 percent of the world's graphite, followed by Brazil and Mozambique.

Figure 1. World graphite reserves and mine production.
Global graphite mine production is concentrated in just a few countries, because of the uneven geographical distribution of graphite reserves.



Source: United States Geological Survey, Mineral Commodity Summaries 2022.

This report provides an overview of the development of graphite-related technologies and how the material is being used in various industries. The overview is based on patent data, which represents an important and well-structured source of information on scientific and technological advancements, as well as being a lead indicator of commercial adoption.

In addition to patent data, the report also incorporates other information, such as country policies and market and business intelligence, in order to provide a multi-faceted, holistic assessment of today's graphite technologies. The report highlights patent examples to illustrate the current state-of-the-art and novel technological advancements.

Types of graphite

Naturally-occurring graphite is formed from carbon-rich organic matter subjected to a high-temperature, high-pressure geological environment for a long period of time. It can be classified into three categories according to degree of crystallinity: namely, amorphous, flake and vein graphite. In addition, there is graphite that has been artificially synthesized.

- **Amorphous graphite**, also called cryptocrystalline or microcrystalline graphite, consists of very fine graphite flakes. Amorphous graphite is the most abundant natural graphite, but occurs at the lowest grade.
- **Artificial graphite**, or synthetic graphite, is a man-made substance manufactured through the high-temperature processing of other carbon materials, such as petroleum coke. Artificial graphite is often purer than natural graphite, but more expensive, due to the large amount of energy consumed during the synthesis process.
- **Flake graphite** is often distributed in the form of isolated, flat crystalline flakes in metamorphic rocks. It is frequently the preferred form of natural graphite in industry and accounts for the majority of natural graphite production globally.
- **Vein graphite**, also known as lump graphite, occurs as veins between rocks. It has a needle-like macro morphology and often exhibits a very high degree of purity and crystallinity. However, vein graphite deposits are rare, such that Sri Lanka is the only country in the world that produces vein graphite in commercial quantities (Touret *et al*., 2018).

All natural graphite sources contain impurities. These include silica, alumina, other oxides and minerals. As a result, natural graphite ores, once mined, need to be put through a series of crushing, grinding, flotation and purification steps in order to produce raw graphite with a high degree of purity. Further processing transforms purified graphite into its various derivatives, such as graphite powder, expanded graphite, spherical graphite and so on. These graphite derivatives possess properties specifically required by specialized applications across industries.

The diverse range of industrial applications for graphite arise from its crystalline structure. As a form of the element carbon, graphite has a layered configuration wherein carbon atoms are arranged in a hexagonal or honeycomb lattice within each layer. Such a unique crystalline structure gives the material several unique properties, such as excellent electrical and thermal conductivity, plus good chemical stability and corrosion resistance.

Uses of graphite

Graphite is widely used in metallurgy, as well as the machinery, electrical, chemical, textile, national defense and other industrial sectors. One of the most important applications of graphite in recent years is as the anode material in lithium-ion batteries (LIBs), which have been increasingly used for energy storage across different industries, as global efforts to address climate change intensify.

The advent of nanotechnology has opened up an abundance of new opportunities for graphite, with graphite-based nanomaterials attracting attention worldwide. In particular, techniques like exfoliation make it possible for atomic layers of bulk graphite to be separated into sheets or platelets only a few nanometers thick. This results in nanosheets, nanoplatelets and single-layer graphite (also known as graphene). These are all new materials with extraordinary properties and great potential. Considered by many to be the new material of the 21st century, graphene in particular has attracted intense global interest for use in emerging fields, such as flexible wearables, superfast electronics, ultrasensitive sensors, multifunctional composites and more.

Global graphite demand is expected to increase significantly over the coming years, due to a rapid adoption of LIBs in the booming electric vehicle (EV) market and the power sector. Demand for graphite for use in EVs and battery storage is forecast to be somewhere between 10 and 30 times its current level by 2040 (IEA, 2022). Graphite's growing importance and its uneven distribution as a resource have raised global concerns. European countries, China and the United States, together with many other countries and international organizations, have listed graphite as either an essential non-metallic raw material or else a strategic key mineral (MNR, 2016; USDC, 2019; AUS, 2019). Besides placing a stronger emphasis on mining and trading policies, governments around the world are ramping up innovation in an effort to support industry in exploiting this critical material.

Structure of the report and methodology

This report examines the graphite-related patent landscape based on relevant patent applications filed from 2012 to 2021, whose publication information was available as of May 30, 2022 (see Annex A, Methodology, for further details). The patent search was conducted using the Orbit Intelligence patent database from Questel. It incorporated several search iterations using queries combining relevant keywords and patent classification codes (see Annex B, Patent searches, for further details). Specifically, the dataset covers primary graphite sources, including flake graphite, amorphous graphite, vein graphite and artificial graphite; major exfoliation techniques for processing graphite; specific graphite derivatives, such as graphite powder, graphite foil/sheet, expanded graphite, and various graphite products and industrial applications, ranging from conductive ink to battery and biomedical applications (Table 1).

Table 1. Scope of the report.

Main categories were first selected then related areas identified.

Main category	Specific area
Graphite source	Amorphous graphite
	Artificial graphite
	Flake graphite
	Vein graphite
Graphite processing	Chemical and mechanical exfoliation
	Electrochemical exfoliation
	Thermal exfoliation
	Ultrasonic exfoliation
Graphite derivatives	Expanded graphite
	Graphene
	Graphite composites/nanocomposites
	Graphite foil/sheet
	Graphite powder
	Micro/nanographite
	Spherical graphite
Graphite uses and applications	Aerospace
	Air purification
	Automotive
	Battery
	Biomedical
	Capacitor
	Carbon brush
	Carbon nanotubes
	Ceramics
	Coating
	Conductive element
	Conductive ink
	Fuel cell

Main category	Specific area
Graphite uses and applications (contd.)	Heat dissipation
	Heat exchange
	Heating element
	Lubrication
	Metal and alloys
	Packaging
	Polymer
	Railway and marine
	Sealing and gasket
	Sensor
	Solar cell
	Structural materials
	Textile
	Water treatment
	Wind power

Note: The taxonomy of the various categories and sub-categories was co-developed with input from subject-matter experts.

The report first looks at patenting activity according to the origin of inventions, so as to identify the top countries/regions for innovation in the graphite space and their respective areas of interest. How the various graphite sources, exfoliation methods and graphite derivatives have been explored in the last decade is then examined, focusing both on the evolution of related patenting activity over time and the filing activity of leading players in each area. The final part of the report applies a specific analysis technique, the Innovation Maturity Matrix, to provide a good overview of the relative maturity of various graphite uses and applications, before undertaking an in-depth analysis of selected graphite application areas.

InfoBox: What we do, what we count, how we count and why

Several general assumptions and methodologies remain constant throughout the analysis. Without specific mention in the text, the following broad definitions and measures have been applied:

- The number of inventions is measured by counting unique patent families, using the FAMPAT patent families defined in Orbit Intelligence as a proxy. Analyses based on unique patent families more accurately reflect invention output; considering individual patent applications instead will inevitably involve double counting, as a patent family may contain several patent publications, if the applicant files the same invention for patent protection in multiple destinations. See Annex A, Methodology, for FAMPAT family construction rules.
- Most analyses refer to numbers of patent families (through a representative patent family member). In the report, the term “patent filings” is used interchangeably with the terms “patent documents,” “inventions” and “patent families.”
- Patent filings do not include utility models.
- Each patent family is counted only once, and the year in which the first member of a patent family was filed counts as the filing year.
- The country or region of origin of an invention is approximated by the earliest priority country, that is, the country where the first member of a patent family was filed. As a result, analysis of country or region of origin does not include patent families whose first members were filed through the Patent Cooperation Treaty (PCT) or with regional patent offices such as the European Patent Office. The omission of such patent families will have had minimal impact on the analysis, as they account for no more than about 1 percent of the overall dataset.