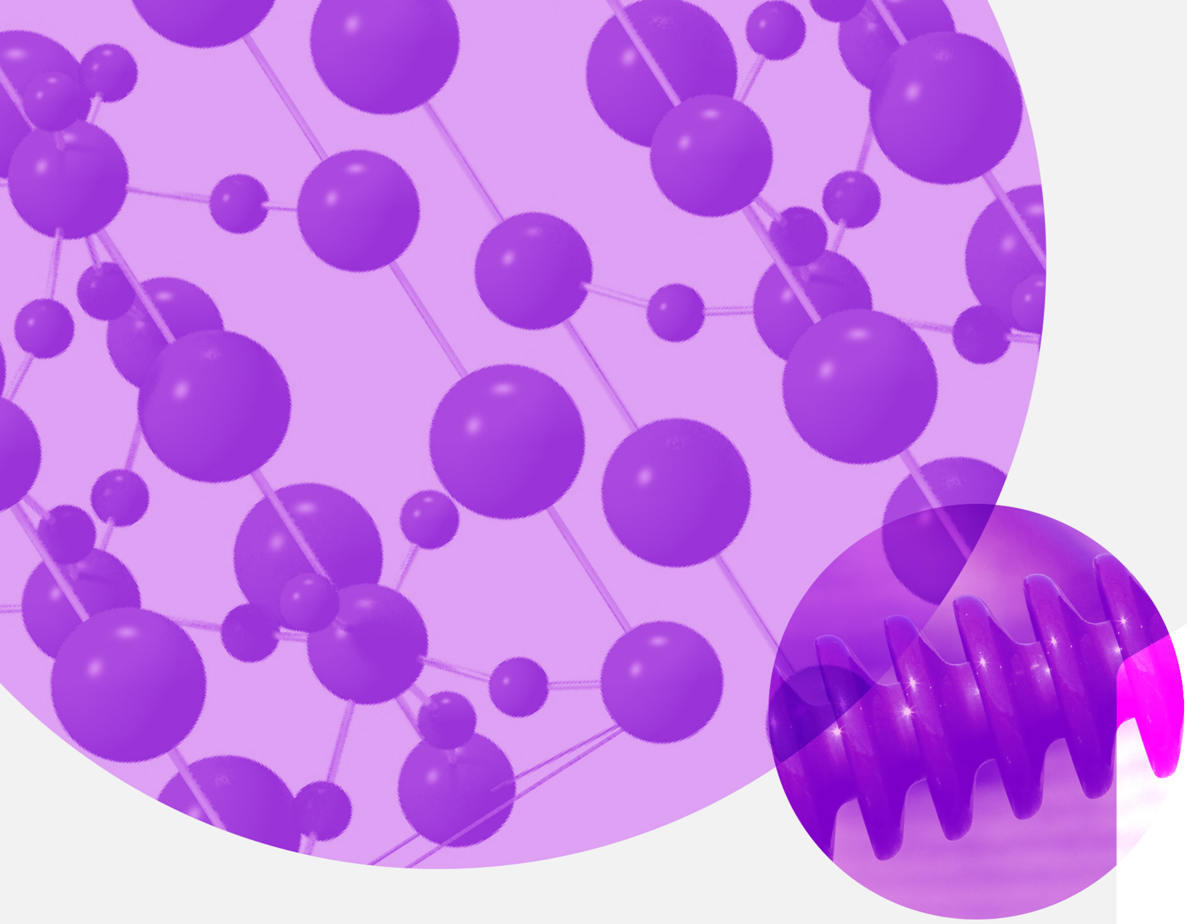

Patent Landscape Report

Production of titanium and titanium dioxide from ilmenite and related applications

WIPO

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Suggested citation: WIPO (2022). *Production of titanium and titanium dioxide from ilmenite and related applications*. Geneva: World Intellectual Property Organization. DOI:10.34667/tind.47029

World Intellectual Property Organization
34, chemin des Colombettes, P.O. Box 18
CH-1211 Geneva 20, Switzerland

ISBN: 978-92-805-3439-9 (print)
ISBN: 978-92-805-3438-2 (online)
ISSN: 2790-7007 (print)
ISSN: 2790-7015 (online)

Cover: Wikimedia, Researchgate.net

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Acknowledgements

This Patent Landscape Report on *Production of titanium and titanium dioxide from ilmenite and related applications* was prepared following a related request from Sri Lanka.

This publication was prepared under the stewardship of Marco M. Alemán (Assistant Director General, IP and Innovation Ecosystems Sector), under the direction of Alejandro Roca Campañá (Senior Director, Technology and Innovation Support Division) and Andrew Czajkowski (Director, Technology and Innovation Support Division), with the generous financial support by Funds-In-Trust Japan Industrial Property Global provided by the Japan Patent Office.

The report was prepared by a project team initially led by Irene Kitsara (IP Information Officer, Technology and Innovation Support Division) and then by Lakshmi Supriya (Patent Analytics Officer, Technology and Innovation Support Division), including Fany Di Lorenzo, Rayhana Laamiri and Nathalie Mantrand-Foussadier (Questel Consulting), and Craig Dsouza (Young Expert Professional, Technology and Innovation Support Division). The project team retrieved and analyzed the data, prepared the visualizations and wrote the report. Thanks also go to Hong Kan (Patent Analytics Officer, Technology and Innovation Support Division) for help with the visualizations.

The report draws on helpful input received during conceptualization of the project and in reviewing the data and report from Professor Nilwala Kottegoda (University of Sri Jayewardenepura, Sri Lanka) and the team at the National Innovation Agency of Sri Lanka: Professor Ajith de Alwis (Chief Innovation Officer/Dean Graduate Studies, University of Moratuwa, Sri Lanka), and Senior Innovation Officers Vindya Wijesinghe, Navodi Wickramasinghe, Thidasi Dahanayake, and Bhagya Herath from NIA circle. Our thanks also go to Julio Raffo (Head, Innovation Economy Section) for reviewing the report and providing valuable inputs.

Finally, our gratitude to the WIPO editorial and design team, including Charlotte Beauchamp (Head, Publications and Design Section) for her invaluable support and advice, Vanessa Harwood for her editorial oversight and Sheyda Navab for the report design.

Further information
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Key findings

Titanium is a metal with high industrial and commercial interest. It is used in many applications in the form of dioxide, elementary metal or in alloys. Titanium is mainly extracted from ilmenite ore (82 percent), other sources being slags (13 percent) and rutile ore (5 percent). About 94 percent of the world's titanium is used to produce titanium dioxide, with the remaining 6 percent being used for titanium metal and alloys. China is the largest producer of titanium dioxide and titanium metal, followed by the United States of America (US) for titanium dioxide and Japan for titanium metal. This report provides a landscape of patenting activity relating to the production of titanium from ilmenite from 2002 to 2022, along with a section on patenting activity for selected industrial applications of titanium and titanium dioxide.

Patenting activity related to titanium dioxide production from ilmenite is rapidly increasing

Between 2002 and 2022, there have been 459 patent families that describe the production of titanium dioxide from ilmenite, and this number is growing rapidly. The majority of these patents describe pre-treatment processes, such as using smelting and magnetic separation to increase titanium concentration in low-grade ores, leading to titanium concentrates or slags. Other patents describe processes to obtain titanium dioxide, either by a direct hydrometallurgical process or through two industrially exploited processes, the sulfate process and the chloride process. Acid leaching might be used either as a pre-treatment or as part of a hydrometallurgical process to directly obtain titanium dioxide or synthetic rutile (>90 percent titanium dioxide, TiO_2). The sulfate process represents 40 percent of the world's titanium dioxide production and is protected in 23 percent of patent families. The chloride process is only mentioned in 8 percent of patent families, although it provides 60 percent of the worldwide industrial production of titanium dioxide. Given the findings from this patent landscape report, we can expect to see industrial chloride process use progressively decrease within the next few years and an increasing use of direct hydrometallurgical processes, which require fewer steps and are more convenient.

Key contributors to patents on the production of titanium dioxide are companies from China, Australia and the United States, reflecting the major contribution of these countries to industrial production. Chinese companies Pangang and Lomon Billions Groups are the main contributors and hold diversified patent portfolios covering both pre-treatment and the processes leading to a final product.

Patenting activity related to titanium metal production from ilmenite remains stable

Between 2002 and 2022, there have been 92 patent families that describe the production of titanium metal from ilmenite, and this number has remained quite steady. These patents describe the production of titanium metal starting from mineral ores, such as ilmenite, and from titanium dioxide (TiO_2) and titanium tetrachloride ($TiCl_4$), a chemical obtained as an intermediate in the chloride process. The starting materials are purified if needed, and then converted to titanium metal by a chemical reduction process using a reducing agent. Processes mainly differ in regard to the reducing agent used to transform the starting material into titanium metal: magnesium is the most frequently cited reducing agent and the most exploited in industrial production.

Key players in the field are Japanese companies, in particular Toho Titanium and Osaka Titanium Technologies, both focusing on reduction using magnesium. Pangang also contributes to titanium metal production and holds patents describing reduction by molten salt electrolysis.

As the patent dynamics are slow in this field and most industrial players describe the standard industrial process, we do not expect a big shift from this process within the next few years. The one emerging technology seems to be molten salt electrolysis developed by Pangang.

Titanium dioxide and titanium metal are used in a wide range of industrial applications

Patents on industrial applications of titanium dioxide and titanium from 2012 to 2022 were analyzed, focusing on six technological domains: ceramics, electrodes for batteries, medical technology, cosmetics, coatings and water treatment.

- **2,027 patent families described the increasing use of titanium dioxide and titanium composites in ceramics**. These materials are used as insulators in electronics, as well as for consumer goods (oven coatings), construction and decoration (tiles). Several leading industrial actors are among the top players, showing the maturity of this technology and its extended industrial use. Among the top industrial players, three are multinational corporations and world leaders in electronic components and devices: TDK, LG and Samsung.
- **1,874 patent families protected the use of titanium dioxide in electrodes and this number is growing rapidly, in part because of the development of electric cars**. Patents mainly focus on the use of titanium-based compounds as cathodes in lithium-based secondary batteries for electronics or automobiles. The presence of several big companies among the top actors shows the maturity of this technology and its broad industrial application. Among the top players, several leading multinational companies of the electronics and automobile industries are present: LG, Samsung, Toshiba, Toyota and Nissan.
- **1,182 patent families cited the use of titanium metal and alloys in medical technology, owing to the high strength-to-weight ratio and chemical stability of titanium, and the number is increasing rapidly.** Implantable products such as bone prostheses, cortical plates, stents and clamps are the most frequently described applications. Some patents also describe coatings for such implantable products and non-implantable surgical devices (guides, robots). Chinese companies and universities dominate this application field, with the Shanghai Jiao Tong University School of Medicine being the top contributor.
- **953 patent families protected cosmetic compositions containing titanium dioxide, mainly used for its opacity and high covering power, as well as an ultraviolet (UV) filter**. Patents cover products for hair coloring/dressing, sunscreen, toothpaste, skin whitening and make-up for skin or lips. The very large presence of big companies among the top actors reflects the high maturity of this technology. French multinational company L'Oréal is the top player with 53 active patents and is followed by several Japanese companies, such as Shiseido and Kao.
- **908 patent families described the use of titanium dioxide and composites in coatings.** This field is dominated by Chinese academic institutions and companies. Konfoong Materials International specializes in coating materials for semiconductors, Zhaoqing Hongwang Metal Industry is a steel manufacturer and Guangzhou UV Technology Material is another coatings manufacturer for glass, photovoltaics and decorative products.
- **719 patent families protected the use of titanium dioxide in water treatment**. This technology is rapidly emerging and expected to grow further within the next few years. Patents describe processes for water treatment, such as electrochemical processes, where titanium dioxide or titanium composites are used as electrodes, or purification by UV irradiation, where titanium dioxide is used as a photocatalyst. Other patents describe a purification technique based on the precipitation of impurities, where titanium tetrachloride is used as a coagulant. Key players are mainly Chinese universities with the exception of China Petroleum Chemical. The lack of industrial contributors reflects the low maturity of this technology and its growth potential.

Context and introduction

Introduction

Titanium extraction from mineral ores

Titanium is the ninth most abundant element on Earth and represents about 0.6 percent of the Earth's crust (Ngugen and Lee, 2019). It is used in several applications, mainly in the form of titanium dioxide, but also as titanium metal, or in alloys. Titanium dioxide is present worldwide in coastal deposits of heavy-mineral sands, which are sources of heavy industrial minerals, such as ilmenite, rutile and leucoxene.

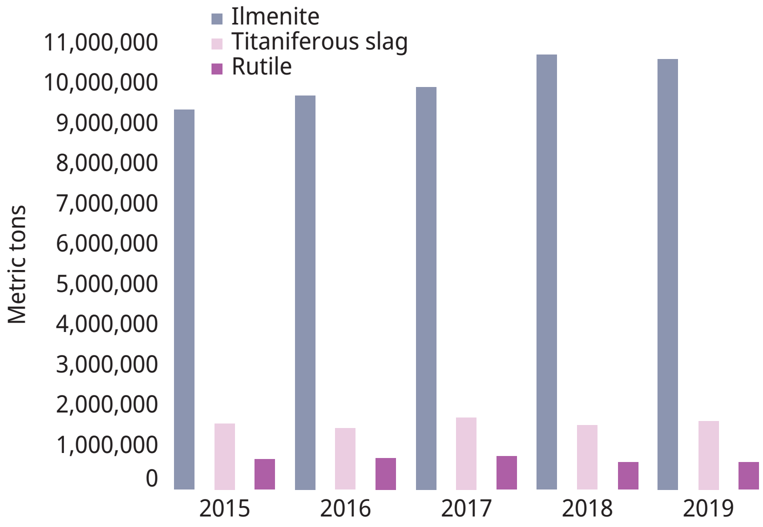
This report provides a landscape of the patent activity related to the process of extracting titanium dioxide or titanium metal from ilmenite ore. In addition, a section on the industrial applications of titanium dioxide and titanium metal is included, focusing on selected applications, such as ceramics, electrodes for batteries, medical technology, cosmetics, coatings and water treatment.

The mineral ilmenite is mainly composed of iron and titanium oxide having an ideal chemical formula $FeTiO_3$ and a stoichiometric content of 53 percent titanium dioxide (TiO_2), although the real TiO_2 content varies between 40 and 65 percent (Van Gosen and Ellefsen, 2018; Ngugen and Lee, 2019). Indeed, weathering can increase the TiO_2 content in titaniferous ores by leaching the iron. Natural rutile contains around 95 percent TiO_2, while leucoxene comprises a mixture of $FeTiO_3$ and TiO_2 with a total TiO_2 content over 65 percent (Ngugen and Lee, 2019).

Ilmenite is commonly processed to obtain a titanium concentrate, which is called "synthetic rutile" if it contains more than 90 percent TiO_2, or more generally "titaniferous slags" if it has a lower TiO_2 content.

More than 80 percent of the estimated global production of titanium concentrate is obtained from the processing of ilmenite, while 13 percent is obtained from titaniferous slags and 5 percent from rutile (Figure 1).

Figure 1. Estimated world production of titanium concentrate by mineral source in metric tons, 2015–2019.
Titanium concentrate is mainly obtained from processing of ilmenite mineral, followed by titaniferous slags and natural rutile.



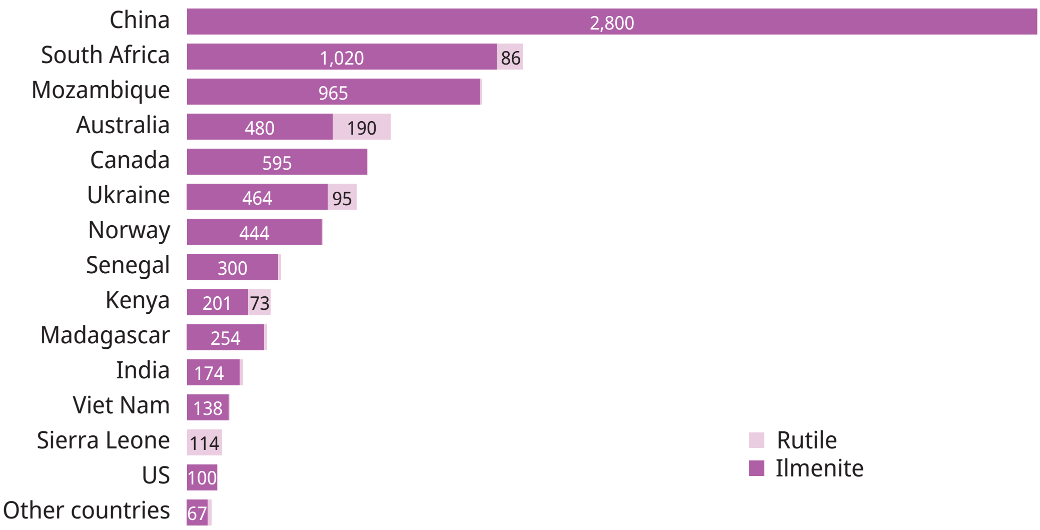
Source: based on data from USGS (n.d.).

Titanium mining and world production

China has by far the highest titanium mining activity (Figure 2). About 35 percent of the world's ilmenite is mined in China, representing 33 percent of total titanium mineral mining (including ilmenite and rutile). South Africa and Mozambique are also important contributors, representing 13 percent and 12 percent of worldwide ilmenite mining, respectively. Australia represents 6 percent of the total ilmenite mining and 31 percent of rutile mining.

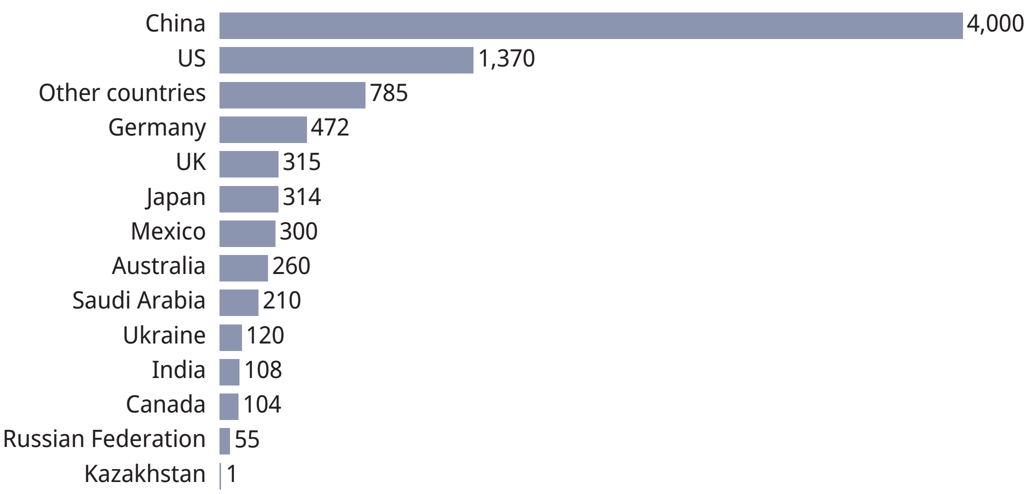
China is the biggest producer of titanium dioxide, followed by the United States and Germany (Figure 3). China is also the leader in the production of titanium metal, but Japan, the Russian Federation and Kazakhstan have emerged as important contributors to this field (Figure 4).

Figure 2. Worldwide mining of the titanium-containing minerals ilmenite and rutile in thousand tonnes of TiO_2 equivalent by country, 2020.
China, South Africa and Mozambique are the biggest contributors to ilmenite mining, while Australia, Sierra Leone and Ukraine are the biggest contributors to rutile mining.



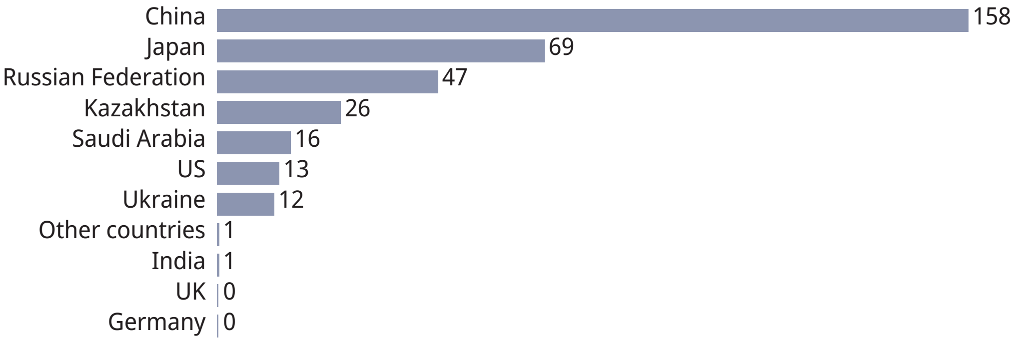
Source: based on data from USGS (n.d.).

Figure 3. Production capacity (in thousand tonnes) of titanium dioxide by country, 2020.
China has the largest production capacity for titanium dioxide, followed by the United States.



Source: based on data from USGS (n.d.).

Figure 4. **Production capacity of titanium metal by country, 2020.**
The main producers of titanium metal are China, Japan and the Russian Federation.

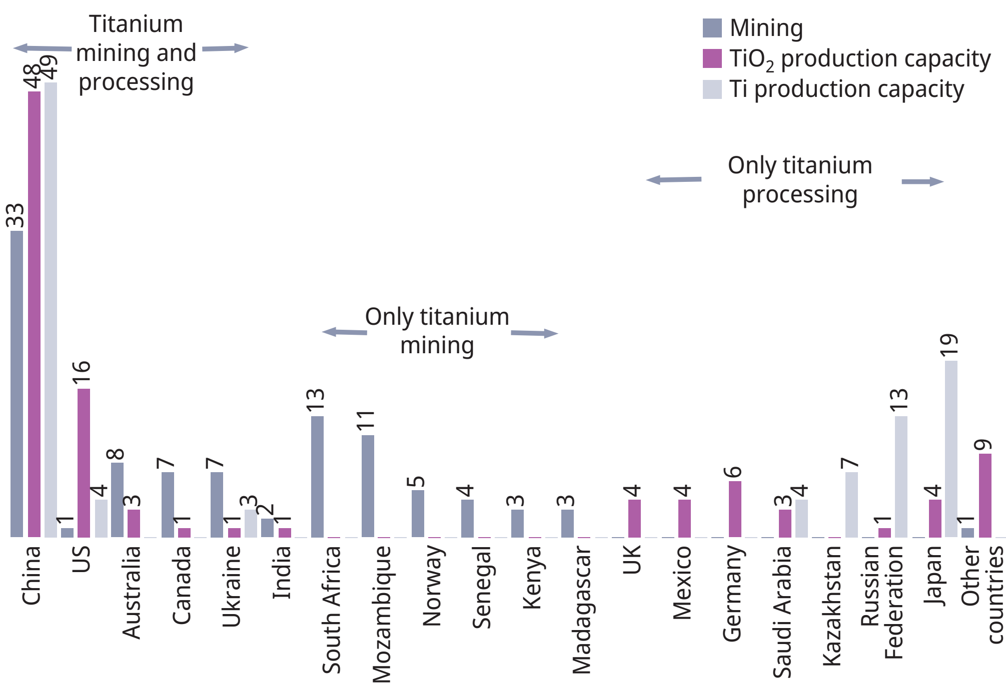


Source: based on data from USGS (n.d.).

Figure 5 compares the contribution of the different countries to the mining of titanium-containing ores and production of titanium dioxide and titanium metal:

- China leads titanium mining and processing, representing 33 percent of worldwide titanium mining and almost 50 percent of total production of titanium and titanium dioxide.
- The United States, Australia, Canada, Ukraine and India are active in both titanium mining and processing.
- South Africa, Mozambique, Norway, Senegal, Kenya and Madagascar are only sources of ores and are not involved in titanium processing.
- Japan, the Russian Federation, Kazakhstan, Saudi Arabia, Germany, Mexico and the United Kingdom (UK) are not involved in mining the natural ores, but are important contributors to the processing of ores or slags and the production of titanium dioxide and/or titanium metal.

Figure 5. **Percentage contribution by country to the mining of titanium-containing ores, TiO_2 production and Ti production (estimated based on production capacity), 2020.**
Some countries contribute both to the mining and processing of titanium (China is the leader). Other countries, mainly in Africa, contribute only to mining, while several Asian and European countries contribute only to processing.



Source: based on data from USGS (n.d.).

This report provides a patent landscape of the processes used to extract titanium dioxide and titanium metal from ilmenite ores. The landscape has worldwide coverage for the years 2002–2022. Patents on extraction of titanium dioxide and titanium metal are categorized according to the starting raw materials used, the type of process described and the final product.

In addition, a section is dedicated to patents describing industrial applications of titanium and titanium-based compounds. Again, this landscape has worldwide coverage and is restricted to active patents from 2012 to 2022. Patent activity was analyzed focusing on six technological fields corresponding to high-tech applications with increasing activity since 2012: ceramics, electrodes for batteries, medical technology, cosmetics, coatings and water treatment.

Production of titanium dioxide

Processing of ilmenite

Overview

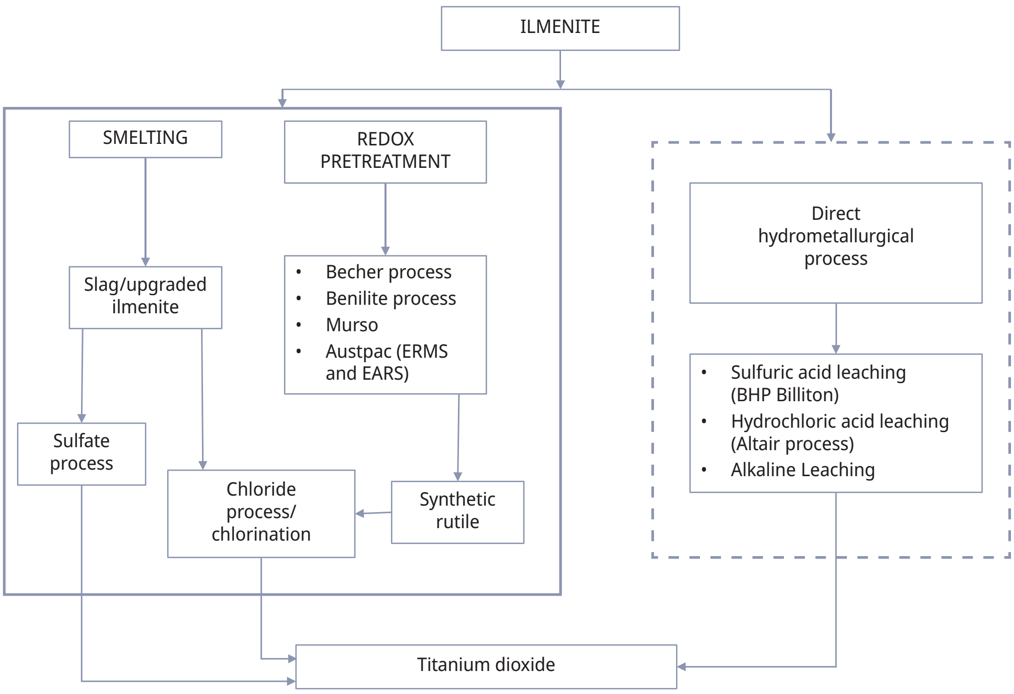
This section focuses on the extraction of titanium dioxide from mineral ores. About 94 percent of the world's titanium consumption in 2020 was used to produce titanium dioxide (USGS, n.d.).

Ilmenite is the most abundant titanium-containing mineral but has a low titanium dioxide content and contains iron along with impurities such as dioxides of chromium, manganese, vanadium, magnesium, aluminum, calcium and silicon (Gázquez *et al.*, 2014).

Sand ilmenite is often processed by smelting or redox pre-treatments to increase its titanium content, leading to "titanium concentrate" or "upgraded slags" (Gázquez *et al.*, 2014). Upgraded slags are commonly treated with the *sulfate process* to obtain titanium dioxide (Figure 6). This process represented around 40 percent of the total TiO_2 production in 2014 (Gázquez *et al.*, 2014).

Other processes, such as the Becher process, have been used to directly transform ilmenite into *synthetic rutile*, which has a TiO_2 content of over 90 percent and can be treated with the *chloride process* to obtain titanium dioxide as the final product (see Figure 6). Overall, the chloride process represented around 60 percent of the world's TiO_2 production in 2014 (Gázquez *et al.*, 2014).

Figure 6. **Different processes leading to titanium dioxide from ilmenite ore.**
Extraction of titanium dioxide from ilmenite ore is commonly achieved by the sulfate and chloride processes after smelting or redox pre-treatments. Hydrometallurgical processes that are more direct with fewer steps are currently in development.



Note: EARS is enhanced acid regeneration; ERMS is enhanced roasting and magnetic separation.
Source: Adapted from Ngugen and Lee (2019).

There is a need to find alternative processes to obtain titanium dioxide from low-grade titanium ores with a reduced waste production and lower economic cost. Recently, some hydrometallurgical processes have emerged that directly obtain titanium dioxide from ilmenite sands or rocks. Hydrometallurgical processes consist of multiple steps, and usually fall into one of two categories: (1) smelting followed by acid leaching at high temperature; (2) redox pre-treatments or roasting followed by acid and/or alkaline leaching (Ngugen and Lee, 2019). A magnetic separation step can be included to increase titanium content.

The sulfate process

The sulfate process represented about 40 percent of the total TiO_2 production in 2014 (Gázquez *et al.*, 2014). In this process, ilmenite is reacted with concentrated sulfuric acid (H_2SO_4). The resulting solution contains titanyl sulfate ($TiOSO_4$) and iron sulfate ($FeSO_4$) dissolved in sulfuric acid. A chemical reduction process is required to ensure that all iron is dissolved. The solution is concentrated, titanium sulfate hydrolyzed and hydrated titanium dioxide precipitated and separated by filtration. The precipitate is calcined, leading to the growth of TiO_2 crystals and removal of residual water and acid (Gázquez *et al.*, 2014).

The general reaction is:

$FeTiO_3 + 2H_2SO_4 \rightarrow TiOSO_4 + FeSO_4 + H_2O$ [dissolution]

$TiOSO_4 + H_2O \rightarrow TiO_2\, nH_2O + H_2SO_4$ [TiO_2 precipitation]

$TiO_2\, nH_2O \rightarrow TiO_2 + nH_2O$ [TiO_2 calcination]

The sulfate process is simple and cheap, can be applied to low-grade ores, and produces a pigment suitable for use in papers, ceramics and inks (Gázquez *et al.*, 2014). However, the quality of product is low and large quantities of waste iron sulfate produced. The overall yield is about 0.5 tonnes of titanium dioxide for approximately 1 tonnes of starting raw ilmenite material (Gázquez *et al.*, 2014).

The chloride process

The chloride process represented nearly 60 percent of total TiO_2 production in 2014 (Gázquez *et al.*, 2014). It can be used for ilmenite, slag or rutile, but commonly natural or synthetic rutile is used, which limits iron waste by-product.

In this process, the raw material is mixed with gaseous chlorine in the presence of coke as a reducing agent. The resulting gas stream contains titanium tetrachloride ($TiCl_4$), carbon dioxides and chlorides of metal impurities (except for silica and zirconium, which are not chlorinated and remain in the reactor). The gas stream is cooled with liquid $TiCl_4$ at a temperature where the other metal chlorides solidify and are separated. The purified $TiCl_4$ stream is further cooled and condensed as liquid, then reacted with oxygen at high temperature to form titanium dioxide and chlorine, which is recycled. Residual chlorine is removed by hydrolysis (Gázquez *et al.*, 2014).

The general reaction process is:

$2TiO_2 + 3C + 4Cl_2 \rightarrow 2TiCl_4 + 2CO + CO_2$ [chlorination]

$TiCl_4$ (gas, impure) $\rightarrow$ $TiCl_4$ (pure, liquid) [purification]

$TiCl_4 + O_2 \rightarrow TiO_2 + 2Cl_2$

The waste produced is mainly coke and unchlorinated solid impurities, along with an acid solution following addition of HCl to the residues of chlorination (Gázquez *et al.*, 2014). Consumption of chloride depends on the amount of iron present in the raw material and hence this process is used only with raw material of a high titanium content.

The Becher process

Ilmenite ores can be upgraded to synthetic rutile by increasing their TiO_2 content to between 90 and 96 percent. In the Becher process, a chemical reduction is applied to iron in the presence of coke, and the material is then leached by ammonium chloride (NH_4Cl) to oxidize and precipitate the iron as dioxide or hydroxide as fine particles, which are then separated from the larger particles of TiO_2 (Gázquez *et al.*, 2014).

Patent landscape

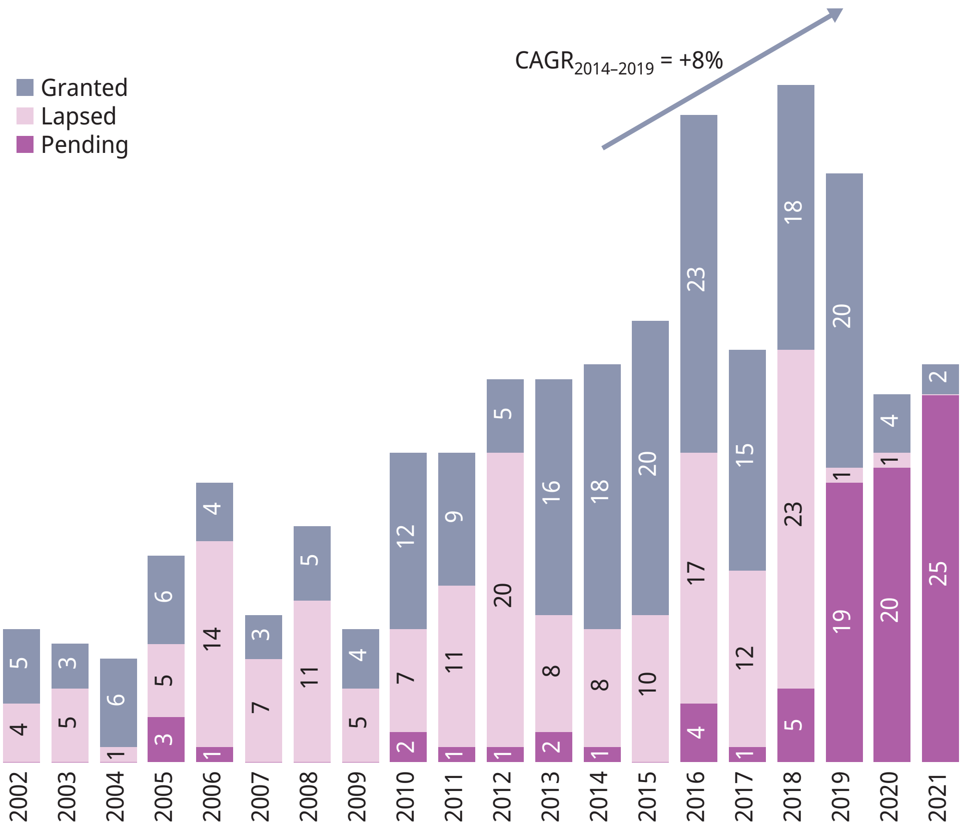
Patent activity

Among the 2,235 patent families obtained from the search, 459 related to the production of titanium dioxide from ilmenite and were considered for in-depth analysis. Non-relevant patents described processes to separate ilmenite from other minerals, the recovery of titanium dioxide from industrial wastewaters, industrial reactors without process description, or analytical methods to measure specific process parameters (see Annex for detailed methodology).

The first filing year of the earliest priority year associated with each patent family is a common metric for patent activity. Patent activity has increased quite steadily since 2012 (compound annual growth rate, $CAGR_{2014–2019}$ = +8 percent) (Figure 7), indicating an increasing interest in the topic. Approximately 44 percent of the relevant patent families have been granted, 19 percent are pending and 37 percent have lapsed. The term lapsed here refers to a patent family where all members are inactive for any reason: that is, expiration of the patent duration, non-payment of annual fees, revocation and so on.

Figure 7. Relevant patent families describing titanium dioxide production from ilmenite, 2002–2021.

Patent activity on titanium dioxide production from ilmenite has increased since 2012.



Note: CAGR is the compound annual growth rate. There is an average 18-month delay between patent filing and publication. 2019 is the last year for which complete data are available. The FAMPAT family definition is used here. A patent family is considered granted if at least one member patent has been granted, pending if no member patent has been granted and the grant decision for at least one member is pending, and lapsed if the none of the patents in the family is active for any reason.

Source: WIPO, based on patent data from Orbit up to April 2022.

Titanium sources, processing and final products

Overview

Patents in this section describe either the whole process for obtaining titanium dioxide from ilmenite, or only specific steps. For example, some patents only describe the processing of the mineral to obtain a slag or concentrate, others describe upgrading slags to a higher titanium content; yet other patents describe the production of titanium dioxide starting from upgraded materials such as processed slags or synthetic rutile.

This report does not include patents describing the production of titanium dioxide from natural rutile mineral, but only from synthetic rutile, which can be an intermediate product in the production of titanium products from ilmenite.

In 55 percent of patent families related to titanium dioxide production, the starting raw material used is ilmenite ore. Since our search was limited to ilmenite ore, the results may be slightly biased. Twenty-nine percent of patent families describe the extraction of titanium dioxide from ilmenite, while in 27 percent of patent families ilmenite is processed to provide upgraded slag or concentrate for further transformation (Figure 8). Ilmenite is also processed to synthetic rutile (8 percent of patent families) or to other intermediate products such as $TiCl_4$ or $TiOSO_4$ (4 percent of patent families).

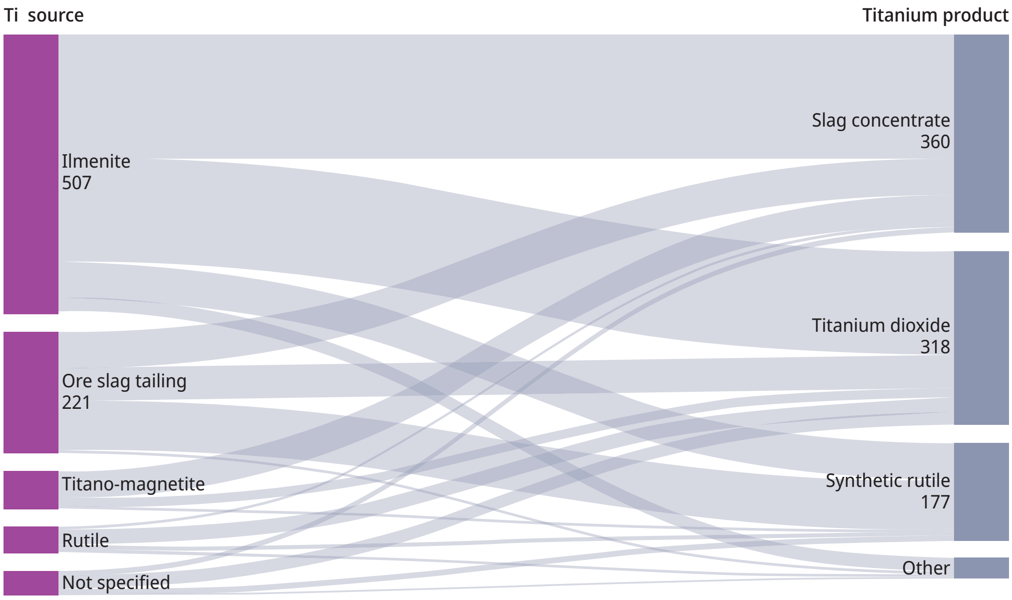
Twenty-five percent of relevant patents cite more generally titaniferous ores or slags as starting material and describe the conversion to titanium dioxide (10 percent), synthetic rutile (9 percent) or simply upgraded slags with increased titanium content (10 percent).

The most cited process is smelting at high temperature, which is mentioned in 43 percent of patents. Smelting is a pre-treatment process and in the majority of patents it leads to the formation of slag or titanium concentrate as the final product (Figure 9). Smelting is combined with magnetic separation in 14 percent of patent families and with acid leaching in 10 percent of patent families. Some patents describe the use of microwave irradiation to homogeneously heat the material to achieve efficient smelting. Redox treatments and roasting are mentioned in 16 percent of patent families and mainly used to obtain synthetic rutile or titanium dioxide rather than slags.

Acid leaching is mentioned in 37 percent of patent families and usually performed by hydrochloric acid, although some inventions describe the use of sulfuric acid. Acid leaching may be a pre-treatment and purification step, in combination with smelting or redox treatments (17 percent of patent families), or part of a hydrometallurgical process to directly obtain synthetic rutile or titanium dioxide (see Figure 9). Leaching at a low acid concentration is commonly used to selectively leach iron and other impurities from ilmenite, leading to an increase in titanium concentration. In contrast, leaching at a high acid concentration is commonly used to leach titanium together with other impurities before subsequent purification.

Figure 8. Categorization of relevant patents according to the titanium source used and the final titanium product.

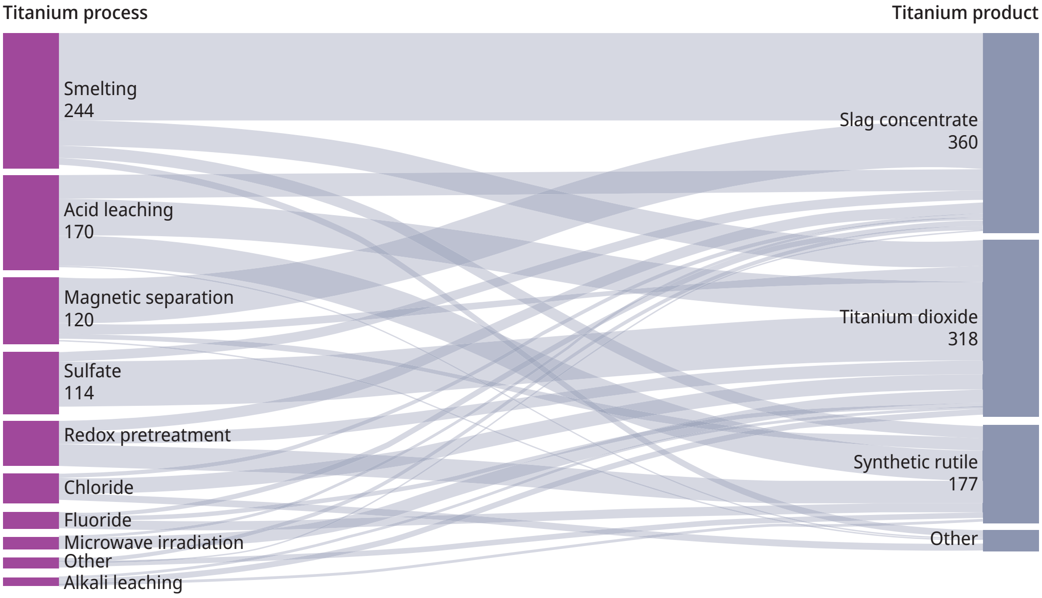
Twenty-nine percent of patents describe the transformation of ilmenite into titanium dioxide, 27 percent describe its transformation into slags and in 8 percent of patents the final product is synthetic rutile. A quarter of innovations describe generic ores, slags or tailings as the starting material and their conversion to synthetic rutile, titanium dioxide or upgraded slags.



Source: WIPO, based on patent data from Orbit up to April 2022.

Figure 9. **Categorization of relevant patents according to the process used and the final titanium product.**

Smelting is mentioned in 43 percent of patent families, is used in combination with magnetic separation and mainly leads to slags. Acid leaching is mentioned in 37 percent of patent families, either as a pre-treatment or as a direct process for obtaining titanium dioxide or synthetic rutile. The sulfate process is protected in 23 percent of patent families and almost exclusively used to obtain titanium dioxide, while the chloride process is only mentioned in 8 percent of patent families.



Source: WIPO, based on patent data from Orbit up to April 2022.

The industrially exploited sulfate process is protected in 23 percent of patent families and is almost exclusively used to obtain titanium dioxide. This process is most frequently cited on its own, although 6 percent of patent families include pre-treatments based on smelting and/or acid leaching.

The chloride process is only mentioned in 8 percent of patent families, although it provided 60 percent of global titanium dioxide industrial production in 2014 (Gázquez *et al.*, 2014). Patents mainly describe the production of titanium dioxide using this process, although some also lead to the production of titanium tetrachloride (denoted as "other" in Figure 9).

The low number of families obtained on the chloride process could be because it requires natural or synthetic rutile of a high purity (>90 percent TiO_2) as a starting material and is not suitable for ilmenite and low-grade ores (Gázquez *et al.*, 2014). Ilmenite can be transformed to synthetic rutile suitable for the chloride process, but only 8 percent of patent families describe this transformation. In the large majority of analyzed patents, ilmenite is directly processed to titanium dioxide or slag, without using synthetic rutile as an intermediate product.

The chloride process is the most suitable for obtaining titanium dioxide from natural rutile, but this ore is far rarer and only 5 percent of the world's titanium is extracted from natural rutile (USGS, n.d.).

Patents protecting more efficient processes for extracting titanium from ilmenite without synthetic rutile as an intermediate product are also present in the dataset. Given the findings in this patent landscape, we can expect the industrial use of the chloride process to progressively decrease in the coming years. The chloride process could be progressively replaced by direct hydrometallurgical processes, which require fewer steps and are more convenient.

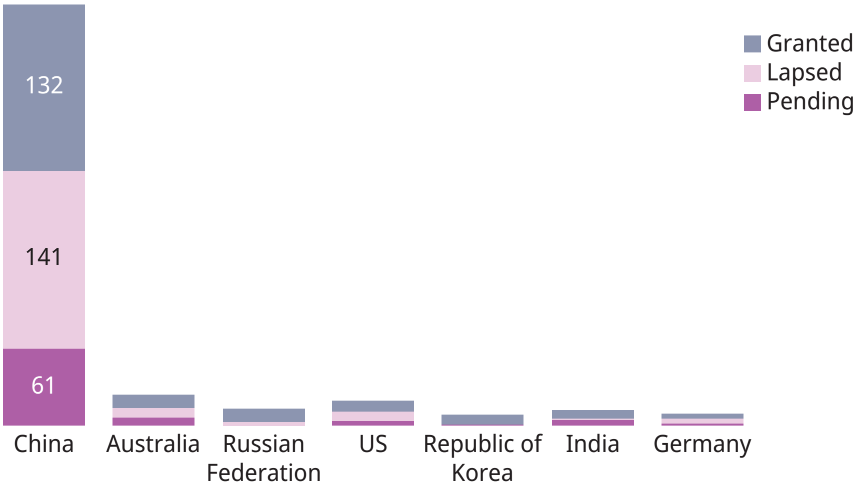
Finally, some patents describe alkaline leaching as an alternative to acid leaching, or a process based on fluoride as an alternative to the chloride process; however, these processes only represent 4 percent of patent families, indicating limited development.

Geographical coverage and key players

China dominates the patent filings in processes for the production of titanium dioxide from titanium, with 73 percent of all patents in our dataset being filed with China as the priority country – that is, the country where the first patent of each patent family is filed (Figure 10). China is followed by Australia (5 percent) and the United States (4 percent).

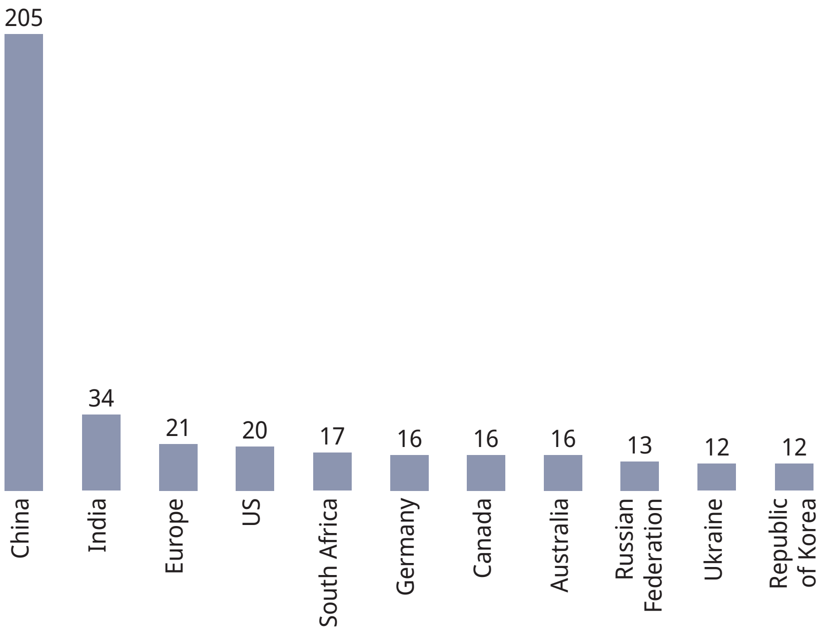
China is also the jurisdiction where most inventions are protected, as 72 percent of all patent families on titanium dioxide production contain a patent that is currently granted in China (Figure 11). India is next, with 12 percent of patent families having a member granted in this country. India is followed by Europe (represented by filings at the European Patent Office (EPO)) and the United States (7 percent of patent families).

Figure 10. Relevant patent families by jurisdiction of first priority.
China is by far the most frequent first priority country for titanium dioxide production. Australia and the United States also have important patenting activity.



Source: WIPO, based on patent data from Orbit up to April 2022.

Figure 11. Relevant patent families by jurisdiction in which at least one family member is granted.
China has the highest number of patents granted, followed by India, Europe and the United States.



Note: Europe represents filings at the European Patent Office (EPO).
Source: WIPO, based on patent data from Orbit up to April 2022.

Patents filed in China generally apply only to China and are not filed internationally, allowing freedom to operate in other countries. Among the 459 relevant patent families related to the production of titanium dioxide, 70 percent cover only China and have only one patent member.

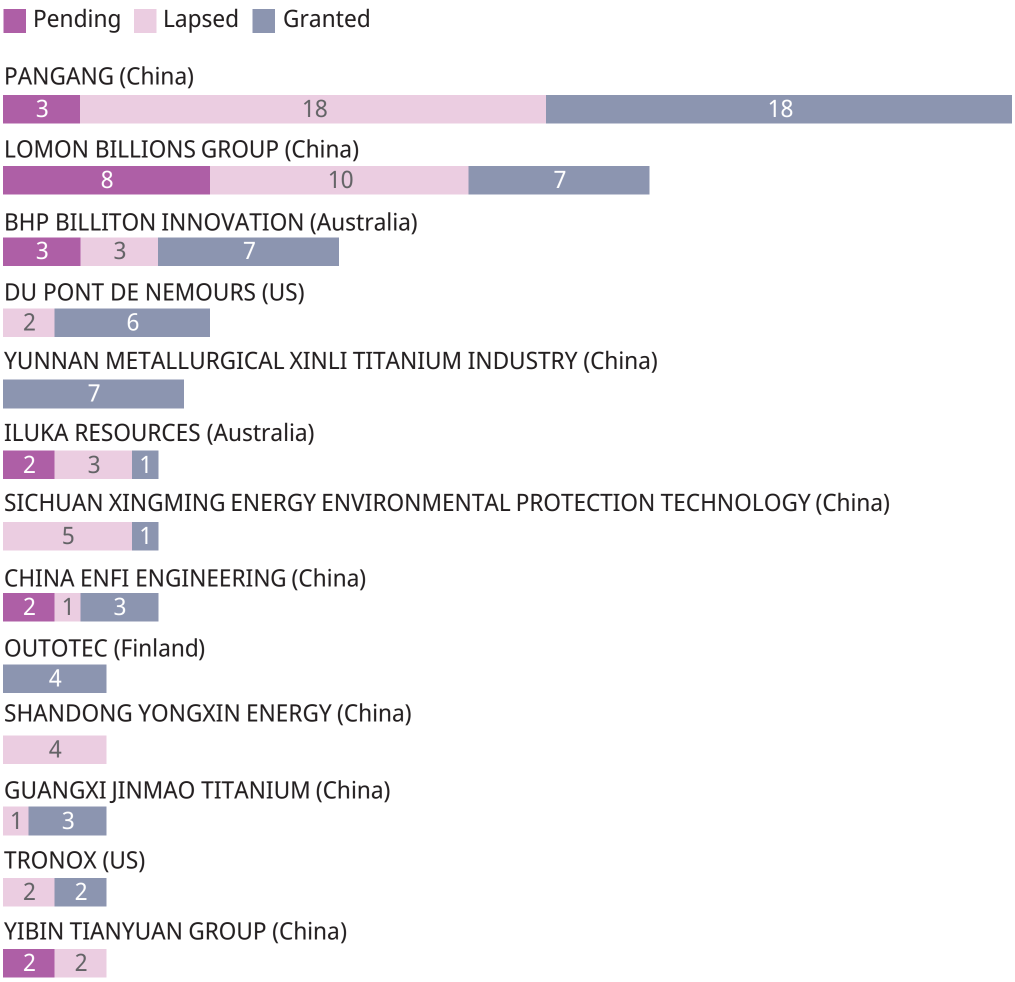
The important role of China in patenting is a reflection of its position as a world leader in both mining and the production of titanium dioxide. India, the United States, Canada, Australia, and Ukraine are well protected by patents and are industrially active both in titanium mining and processing (Figure 5). Mexico is involved in the production of titanium dioxide, but does not have much patent protection. By contrast, in the Republic of Korea, inventions are well-protected by patents, but it is not a significant contributor to titanium mineral mining or titanium production (see Figure 5).

Key players in the extraction of titanium dioxide from ilmenite comprise an almost equal mix of both industrial and academic players and are mainly from China. Most patents are filed by single applicants, although there are some collaborations between Chinese companies and academics.

The Chinese company Pangang emerges as the main contributor to patents for processing of the mineral to obtain titanium dioxide (Figure 12). It holds patents covering pre-treatments, in particular smelting, and the two industrially exploited sulfate and chloride processes. Pangang also holds patents for less common processes, such as the use of microwave irradiation to achieve more homogeneous heating, the use of alkali leaching as an alternative to acid leaching, and a process based on fluoride as an alternative to chloride (Figure 13).

Pangang has collaborated with the Institute of Process Engineering of the Chinese Academy of Science on one patent focusing on the preparation of high-titanium slag.

Figure 12. **Industrial key players in the production of titanium dioxide.**
Key industrial players reflect the contribution of China, Australia and the United States to titanium dioxide production.



Source: WIPO, based on patent data from Orbit up to April 2022.

Figure 13. **Industrial key players in titanium dioxide production and the processes described in their patents.**

Pangang and Lomon Billions Group have diversified portfolios covering pre-treatments and final processes; BHP Billiton Innovation focuses on a modified sulfate process; Yunnan Metallurgical Xinli Titanium Industry specializes in the chloride process; Shandong Yongxin Energy specializes in the use of microwave irradiation as homogeneous heating for smelting.

Company	Country	Smelting	Acid leaching	Sulfate	Redox treatment	Alkali leaching	Chloride	Fluoride	Magnetic separation	Microwave irradiation
PANGANG	China	25	10	5	6	4	3	1	4	1
LOMON BILLIONS GROUP	China	16	10	8	3	2	3	1	6	
CHINA ENFI ENGINEERING	China	6					3		1	
SHANDONG YONGXIN ENERGY	China	4							4	4
OUTOTEC	Finland	4							4	
YIBIN TIANYUAN GROUP	China	2	4		1		1	1	1	
DU PONT DE NEMOURS	US	2	1		5				0	
SICHUAN XINGMING ENERGY ENVIRONMENTAL PROTECTION TECHNOLOGY	China	1			5					
YUNNAN METALLURGICAL XINLI TITANIUM INDUSTRY	China						7			
TRONOX	US		2	3	1				1	
ILUKA RESOURCES	Australia			1	5					
GUANGXI JINMAO TITANIUM	China		2	2						
BHP BILLITON INNOVATION	Australia		4	13	1					

Source: WIPO, based on patent data from Orbit up to April 2022.

Pangang's patent portfolio is the largest and the most diversified, although its patents do not extend to countries outside China, and only 53 percent are active.

The large patent portfolio of Pangang reflects its leading position in the industrial production of titanium dioxide, with a yearly production of approximately 220,000 tonnes (Reuters, 2020), compared to a total production capacity of 4 million tonnes in China and 8 million tonnes worldwide (USGS, n.d.).

Other Chinese companies such the Lomon Billions Group, Yunnan Metallurgical Xinli Titanium Industry and China Enfi Engineering are key players (see Figure 12).

Lomon Billions Group is another Chinese company holding a patent portfolio similar to that of Pangang, although smaller and covering pre-treatments, as well as the sulfate and the chloride processes. It holds a patent with the Institute of Multipurpose Utilization of Mineral Resources of the Chinese Academy of Geological Sciences focusing on the upgrading of a titanium slag. Lomon Billions' patents are protected only in China.

The Chinese company Yunnan Metallurgical Xinli Titanium Industry is the biggest contributor to patents on the chloride process and its portfolio covers exclusively this technique. All its patents are active but protection does not extend outside China.

Finally, the Chinese company Shandong Yongxin Energy emerges as the main user of microwave irradiation for homogeneous heating, all its patents combining microwave irradiation, smelting and magnetic separation. These patents are only protected in China and not extended to other countries, as typically observed for applications by Chinese companies in this field.

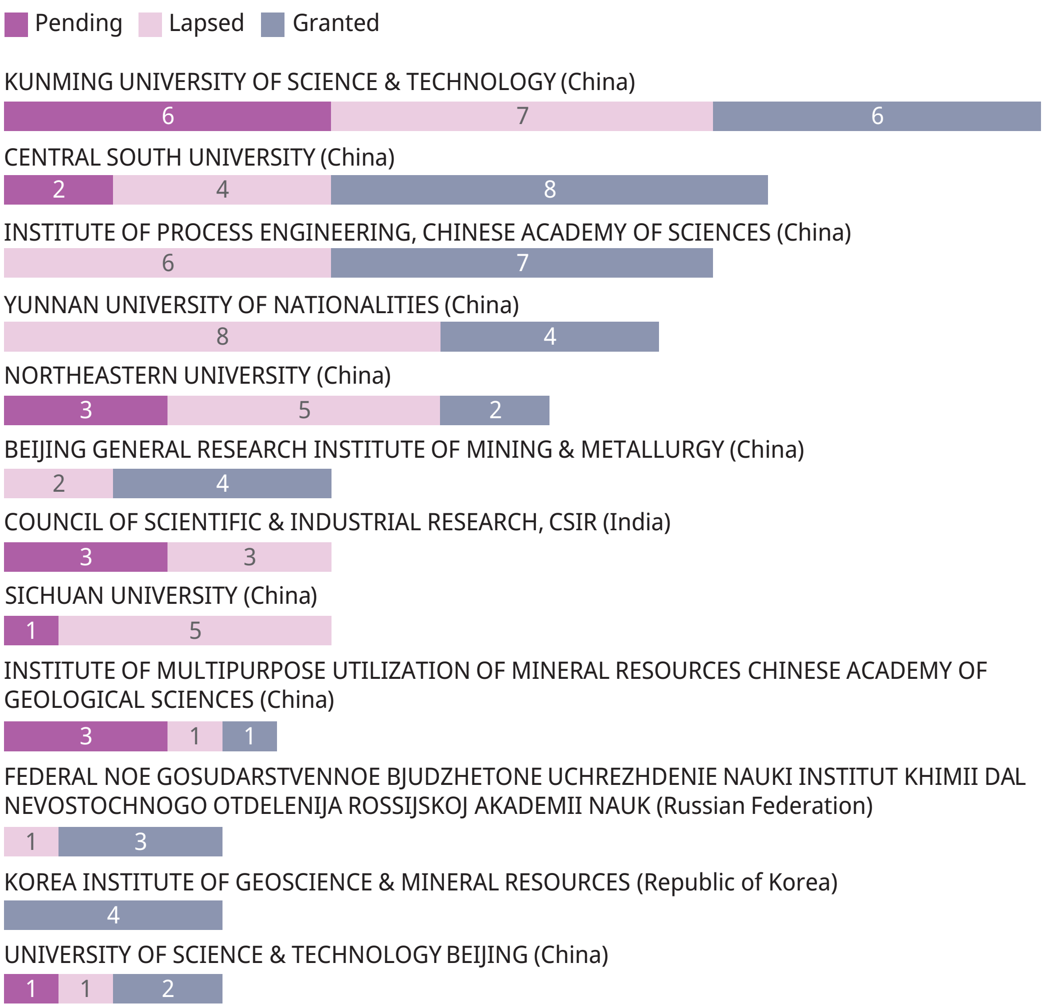
Australia is represented by BHP Billiton Innovation and Iluka Resources. BHP Billiton Innovation holds several patents based on a modified sulfate process. Their patents are filed in China, Europe, the United States and also other countries such as India and Brazil. Iluka Resources specializes in the production of synthetic rutile starting from ilmenite, using processes based on redox treatments. Some of their patents are also filed in Brazil, Canada, China, Europe, India and the United States.

Du Pont de Nemours is a key player from the United States, and has developed processes to directly produce titanium dioxide from ilmenite, mainly based on redox reactions. Its patents are mainly filed in the United States, Europe and Australia.

Key players from China, Australia and the United States reflect the contribution of these three countries to titanium dioxide industrial production. No German industrial actor emerges in the top players, although Germany has a significant production capacity (Figure 3). One Finnish company, Outotec, is present among the key players, although Finland does not emerge as a major producer of titanium dioxide (see Figure 3).

Among the non-industrial players, several Chinese universities and public research institutes are present, although none emerges as the overall leader (Figure 14). Among the non-Chinese contributors are public research institutes from India, the Russian Federation and the Republic of Korea. The patent activity of Chinese, Indian and Russian public institutes reflects the industrial activity of these countries. By contrast, the Republic of Korea does not emerge as a significant contributor to titanium production (see Figure 3).

Figure 14. Academic and public institutions having significant patent activity in titanium dioxide production.
The patent activity of Chinese, Indian and Russian public institutes reflects the industrial activity of these countries. The Republic of Korea is a key player in patents, but does not emerge as a significant contributor to titanium production.



Source: WIPO, based on patent data from Orbit up to April 2022.

Production of titanium metal

Processing

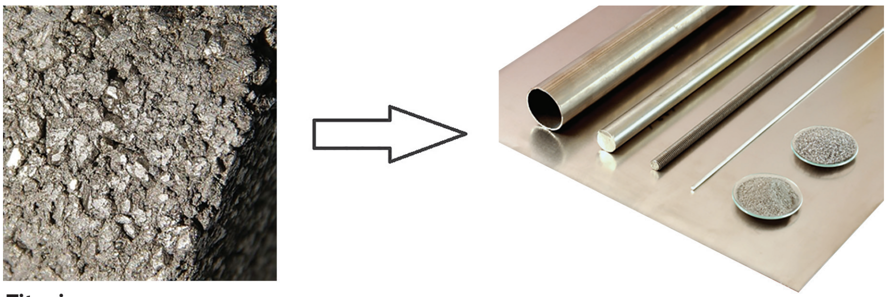
Overview

Titanium metal is a silver-white metal not found in nature, because of its strong affinity to oxygen, carbon and nitrogen. It has low density, good strength, excellent corrosion resistance to salt and acids, and low electric and thermal conductivities (El Khalloufi *et al.*, 2021).

Titanium metal is used in many different applications owing to its special properties. The most common titanium alloy is Ti6A-4V (90 percent titanium, 6 percent aluminum, 4 percent vanadium) and typically used in medical implants (El Khalloufi *et al.*, 2021).

The production of titanium metal represents only a small fraction (6 percent in 2020) of total titanium consumption, with the remainder being industrially exploited as titanium dioxide. Titanium metal is commonly obtained in the form a sponge, which can be reprocessed to obtain compact metal, such as ingots or billets, or a fine powder (Figure 15).

Figure 15. **Different forms of titanium.**
Titanium sponge is the most common form of the metal, which can be processed to obtain different products such as rods, ingots, and titanium metal powder.



Source: (left-hand image) https://commons.wikimedia.org/wiki/File:Titanium_sponge_cylinder,_120_grams.jpg
(right-hand image) adapted from https://commons.wikimedia.org/wiki/File:Titanium_products.jpg

Processes

For the production of titanium metal, titanium dioxide (TiO_2) or titanium tetrachloride ($TiCl_4$) derived from the chloride process are typically used. The standard industrially used process is the *Kroll process* first developed by Du Pont Germany in 1848 (El Khalloufi *et al.*, 2021). The *Hunter* and *Armstrong* processes are also commercially used, but not considered economically competitive (El Khalloufi *et al.*, 2021).

The Kroll process

The Kroll process uses $TiCl_4$ produced by the chloride process as the starting material (El Khalloufi *et al.*, 2021). Titanium is reduced by the addition of metallic magnesium (Mg). Mg and magnesium chloride ($MgCl_2$) are then separated by vacuum distillation or helium sweeping followed by leaching. Mg is then recycled by electrolysis of $MgCl_2$. A sponge of titanium metal is obtained as the final product:

$$2TiCl_4\,(\text{liquid}) + 2\,Mg\,(\text{solid}) \rightarrow Ti\,(\text{solid}) + 2\,MgCl_2\,(\text{liquid})\ [\text{reduction}]$$

$$MgCl_2\,(\text{liquid}) \rightarrow Mg\,(\text{solid}) + Cl_2\,(\text{gas})\ [\text{recycling by electrolysis}]$$

The Hunter and Armstrong processes

The Hunter and Armstrong processes are similar to the Kroll process, but sodium (Na) is used to reduce titanium instead of magnesium (El Khalloufi *et al.*, 2021). These processes are more expensive, because four molecules of sodium are required to reduce one molecule of titanium tetrachloride or titanium dioxide, whereas only two molecules of magnesium are required for the same purpose. Recovering sodium by electrolysis is as expensive as recovering magnesium, and this makes the process using sodium more expensive, although the purity of the obtained titanium powder is higher (99 percent) (El Khalloufi *et al.*, 2021).

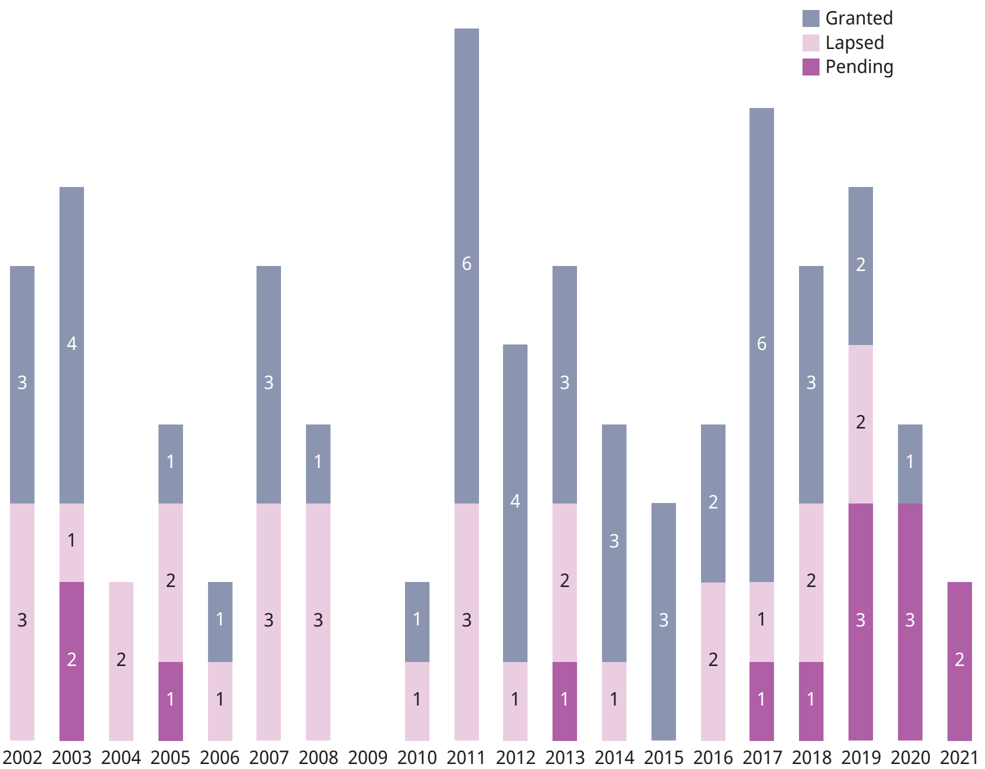
Patent landscape

Patent activity

Among the 304 patent families found, 92 related to the production of metal titanium and were considered for in-depth analysis. Of these about half (52 percent) were granted, 15 percent pending and 33 percent lapsed.

Patent activity on titanium metal production has remained quite steady since 2002, indicating a constant but not significantly growing interest in the topic (Figure 16).

Figure 16. **Number of relevant patent families based on first priority year, 2002–2021.**
Patent activity related to titanium metal production from ilmenite has been steady since 2002.



Note: There is an average 18-month delay between patent filing and publication. 2019 is the last year for which complete data are available. There was no relevant patent activity in the year 2009.

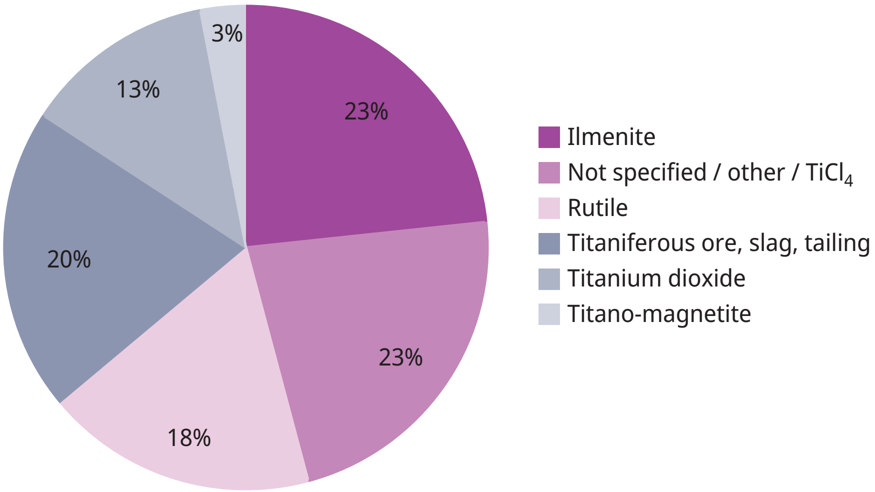
Source: WIPO, based on patent data from Orbit up to April 2022.

Titanium source, process and product

Patent families for the production of titanium metal were categorized according to the starting material, the reducing agent used to reduce the starting material to titanium metal, and the final form of titanium metal product.

The starting material used is ilmenite, rutile (synthetic or natural), titanium dioxide or more generally, titaniferous ore or slag (Figure 17). Some patents do not specify the source of titanium; others use the titanium tetrachloride ($TiCl_4$) produced with the chloride process as a starting material.

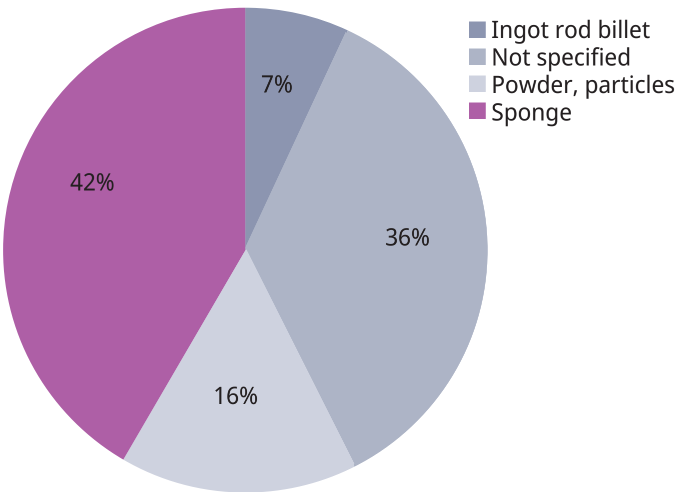
Figure 17. **Titanium metal production according to titanium source.**
Titanium metal can be obtained not only starting from ilmenite, rutile, slags and titanium dioxide, but also from $TiCl_4$ obtained by the chloride process.



Source: WIPO, based on patent data from Orbit up to April 2022.

The main final product is a titanium metal sponge (42 percent of patent families). In 16 percent of patent families, a powder or a particulate is obtained and in 7 percent further processing is required to obtain compact titanium in the form of ingots, rods or billets (Figure 18).

Figure 18. **Titanium metal production according to titanium final product.**
Titanium metal is usually obtained in the form of a sponge, but can be reprocessed to obtain a powder or ingots.



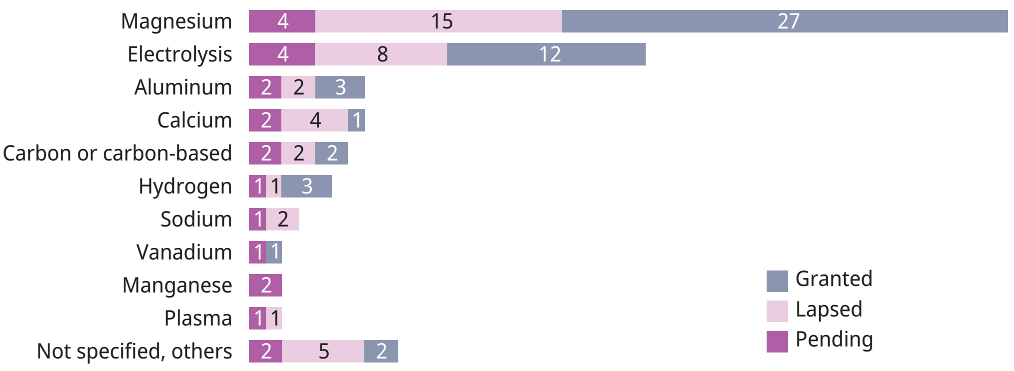
Source: WIPO, based on patent data from Orbit up to April 2022.

For the reduction of the starting material to metallic titanium, magnesium is used in about 50 percent of patent families, reflecting the broad industrial use of the Kroll process (Figure 19). Other patents describe the use of other multivalent metals, such as aluminum (7 percent of patent families), calcium (7 percent), manganese (2 percent) or vanadium (2 percent). The use of magnesium and calcium in combination is also described.

The use of monovalent sodium is only described in 3 percent of patent families, although the Hunter and Armstrong processes are commercially used. The interest in reduction methods with monovalent metals seems very limited, probably because of its higher cost.

About one-quarter (26 percent) of patent families describe obtaining titanium dioxide by molten salt electrolysis.

Figure 19. **Patent families categorized according to reducing agent.**
Magnesium is described as a reduction agent in half of patent families, but some patents mention the use of other metals (aluminum, calcium, manganese or sodium). Reduction by electrolysis is cited in 26 percent of patent families.



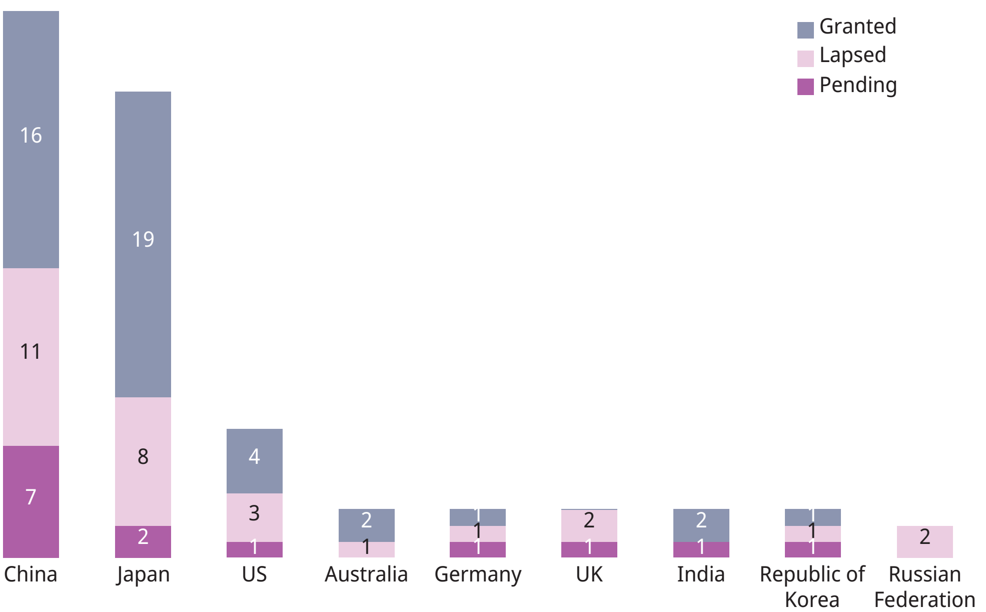
Source: WIPO, based on patent data from Orbit up to April 2022.

Other non-metallic reducing agents described are hydrogen (5 percent), used alone or in combination with vanadium, and coke or carbon-based reducing agents (6 percent).

Geographical coverage and key players

China and Japan are the most frequent jurisdictions where the first patent application of each patent family was filed. China and Japan are the first priority countries in 37 percent and 32 percent, respectively, of patent families related to titanium metal production (Figure 20).

Figure 20. **Relevant patent families by country of first priority.**
China, Japan and the United States are the most frequent first priority countries.



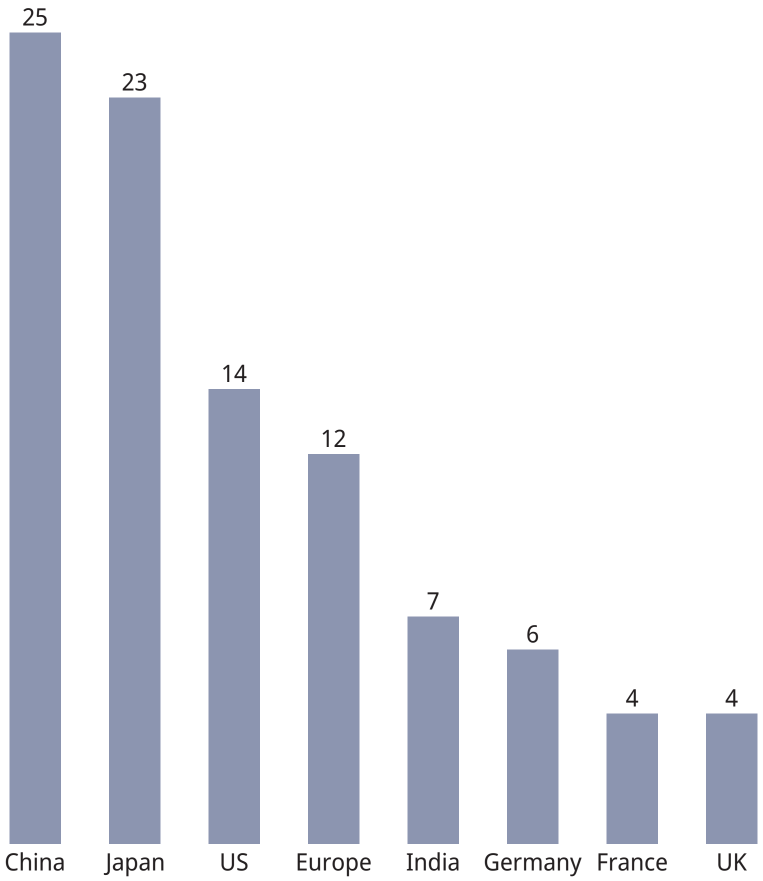
Source: WIPO, based on patent data from Orbit up to April 2022.

The significant contribution of China and Japan to patents related to titanium metal production reflects their important role in titanium metal industrial production. Japan emerges as a key contributor to titanium metal production, although its patenting and industrial activity in the fields of titanium dioxide production and mining is very limited (Figure 5). The United States is also an important first priority country, although its industrial activity in titanium metal production is minor (Figure 5).

The countries with the highest number of granted patents are China, Japan and the United States, reflecting the important industrial production capacity of these countries (Figure 21). Patents

Figure 21. Number of relevant patent families by country, where at least one family member is granted.

China, Japan and the United States are where most patents are granted, followed by in Europe (EPO).



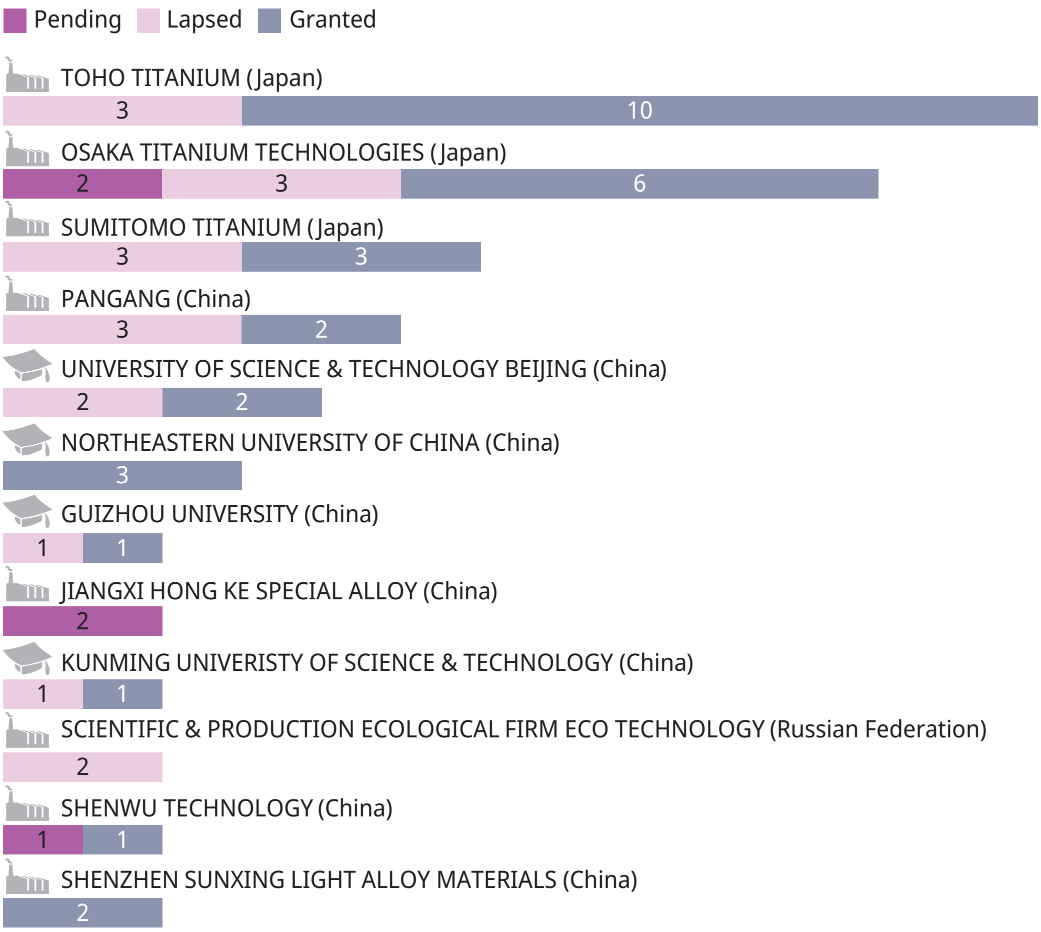
Note: Europe represents filings at the EPO.
Source: WIPO, based on patent data from Orbit up to April 2022.

filed in China and Japan frequently cover only those countries and are not filed internationally: 28 percent of relevant patent families cover only China and 22 percent only Japan.

Inventions are also protected in Europe and India by a significant number of granted patents, although no major industrial activity is present in either. By contrast, the Russian Federation and Kazakhstan are important contributors to titanium metal production, but do not feature among those countries with the highest number of granted patents.

Key players in the production of titanium metal mainly comprise companies, although some Chinese universities are also present (Figure 22). Patents were most frequently filed by single applicants, although some companies collaborated. Japanese companies Toho Titanium, Osaka Titanium Technologies and Sumitomo Titanium are the main contributors to patents related to titanium metal production, making Japan the leading country in this field (see Figure 22). Osaka Titanium Technologies and Sumitomo Titanium have collaborated on a patent protecting the use of calcium as reduction agent. Their patents were frequently filed only in Japan, with the exception of one pending application in Europe.

Figure 22. Industrial and academic key players in the production of titanium metal.
Apart from industrial actors, there are also several Chinese universities among the top players.



Source: WIPO, based on patent data from Orbit up to April 2022.

Pangang, the leading company in the production of titanium dioxide, holds patents describing production of titanium metal by electrolysis or using coke as a reducing agent. Some of their patents are extended to the United States, Japan and Germany, in contrast to their patents on titanium dioxide, which were only filed in China. This might be because of the important role of Japan in the industrial production of titanium metal.

The other key players mainly consist of Chinese universities and companies, with the exception of a Russian company, which only owns two lapsed patent families.

Industrial key players in the production of titanium metal frequently described the use magnesium as a reducing agent, reflecting the most widely used industrial production method (Figure 23).

Because of the limited interest in methods to obtain titanium metal from ilmenite and the fact that most industrial players describe the standard, industrially used processes, we do not expect a big shift away from this process in the coming years. The only emerging technology seems to be molten salt electrolysis, with Pangang driving its development.

Figure 23. **Industrial key players in the production of titanium metal categorized according to the reducing agent used.**

Industrial key players mainly use magnesium as the reducing agent, with the exception of Pangang, which focuses on electrolysis and reduction with coke, and Shenzhen Sunxing Light Alloy Materials, which uses aluminum.

Company	Country	Magnesium	Aluminum	Calcium	Carbon or carbon-based	Electrolysis	Sodium	Not specified
TOHO TITANIUM	Japan	13						
OSAKA TITANIUM TECHNOLOGIES	Japan	8		3				
SUMITOMO TITANIUM	Japan	5		1				
PANGANG	China	0			1	3		1
JIANGXI HONG KE SPECIAL ALLOY	China	1					1	
SCIENTIFIC & PRODUCTION ECOLOGICAL FIRM ECO TECHNOLOGY	Russian Federation	2						
SHENWU TECHNOLOGY	China	2						
SHENZHEN SUNXING LIGHT ALLOY MATERIALS	China		2					

Source: WIPO, based on patent data from Orbit up to April 2022.

Industrial applications of titanium dioxide and titanium

Overview

About 94 percent of the world's titanium in 2019 was used to produce titanium dioxide and about 6 percent used to produce titanium metal and titanium alloys (USGS, n.d.).

Titanium dioxide is mainly used to produce pigments for paints, paper and the plastics industry (USGS, n.d.). For the rest, titanium dioxide is used in the chemical industry for the manufacturing of carbides and other compounds.

Titanium metal and alloys are used for the following:

- the production of spacecraft and missiles in the aerospace and military industries, because of their strength-to-weight ratio;
- coatings for ships and seawater-cooled power plants, because of their high resistance to salt corrosion;
- a catalyst in petroleum refineries and in the chemical industry;
- the production of artificial joints, stents and surgical instruments in the medical industry;
- lightweight consumer goods and sports equipment, such as jewelry, golf clubs and bicycles (El Khalloufi *et al.*, 2021; Ngugen and Lee, 2019).

Patent landscape

The patent landscape for the industrial applications of titanium dioxide and titanium metal is very large, reflecting the broad use of these compounds in very different fields. The search, limited to granted or pending patents from 2012 to 2022 in order to focus on the most recent applications and to estimate emerging trends in the next few years, led to a collection of 53,754 patent families. From this dataset, some specific technological domains were selected for in-depth analysis. These domains were chosen according to the type of patent (focusing on products and excluding processes, analysis methods and general compositions without a specific application), with a preference for "high-tech" applications and for emerging technologies, as reflected by the variation in patent activity since 2012 (see Annex for details).

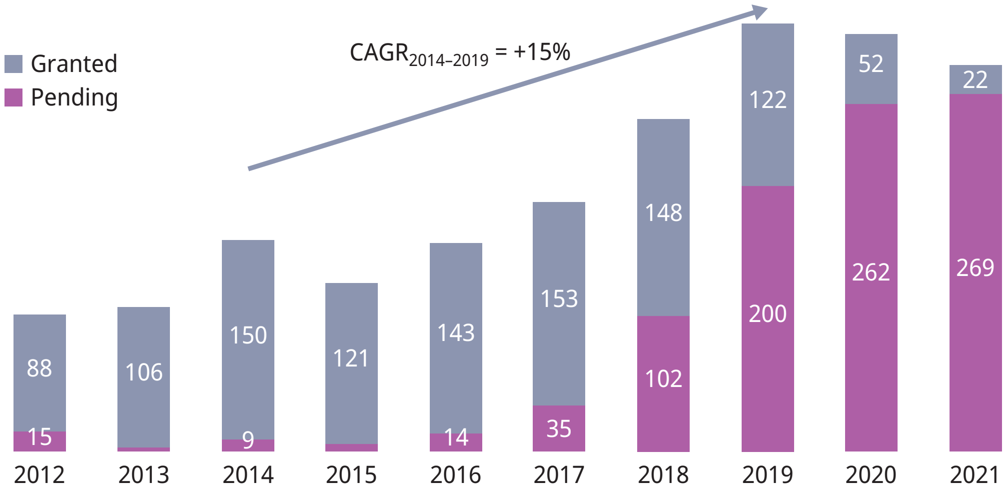
The application domains selected for in-depth analysis cover the use of titanium dioxide, titanium metal and alloys in ceramics, as electrodes for batteries, in medical technology, in cosmetics, as coating materials and for the treatment of water and wastewater.

Ceramics

Patent activity

Between 2012 and 2022, there were 2,027 active patent families describing the use of titanium dioxide and titanium in ceramics (Figure 24). Patent activity shows a growing interest in ceramics as an industrial application of titanium since 2016, with a CAGR of +15 percent between 2014 and 2019.

Figure 24. **Patent families in ceramics based on first priority year, 2012–2021.**
Patent filings related to the use of titanium and titanium dioxide in ceramics have strongly increased since 2012.



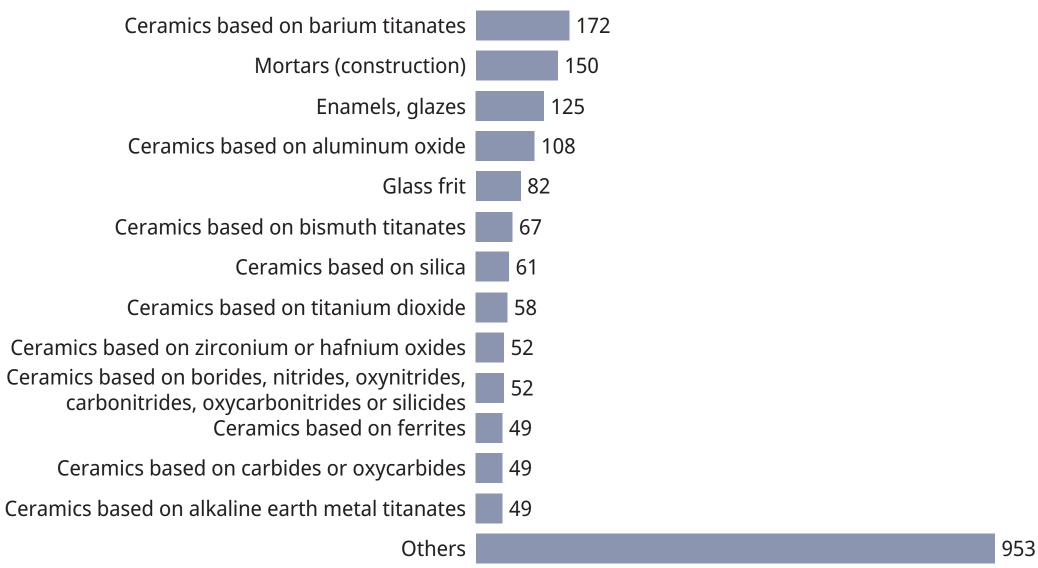
Note: CAGR is the compound annual growth rate. There is an average 18-month delay between patent filing and publication. 2019 is the last year for which complete data are available.
Source: WIPO, based on patent data from Orbit up to April 2022.

Patent content

Patents on the application of titanium and titanium dioxide in ceramics describe novel ceramic compositions. Among the 2,027 patent families in the field of ceramics, 337 mention terms related to nanotechnologies, such as nanostructure, nano powder or nanoparticles.

Patent families related to ceramics can be classified into different categories according to their principal International Patent Classification (IPC) codes, which mainly reflect the chemical composition of the products (Figure 25). Titanium dioxide is frequently used in combination with other metals (barium, aluminum, bismuth, zirconium, hafnium and iron, but also vanadium, niobium, tantalum, molybdenum, strontium, zinc, tin and rare earth metals, included in "others" in Figure 25) and oxides, or non-metallic elements (silicon, boron, nitrogen and carbon, but

Figure 25. **Classification of patent families related to ceramics according to their application area.**
Ceramics include a variety of different applications.



Source: WIPO, based on patent data from Orbit up to April 2022.

also phosphorous, included in “others” in Figure 25) and their oxides. In addition, titanium-based products are classified according to their application as mortars for construction and coating material such as enamels and glazes. These coatings might facilitate cleaning, increase brightness and strength, or have anti-bacterial properties. They can be used for ovens and cookware or car components.

Geographical coverage and key players

China is leading the patent activity on ceramics, with 83 percent of patent families having China as the first priority country (Figure 26), followed by Japan and the Republic of Korea. Chinese patenting activity is marked by a strong domestic environment: 80 percent of patent families describing the use of titanium in ceramics are filed exclusively in China.

The United States and European countries have between them less than 50 active patent families related to titanium applications in ceramics, but tend to protect their inventions in other countries.

China is by far the country with the highest number of granted patents, followed by Japan, the United States, the Republic of Korea and Europe (Figure 27).

Chinese universities are very active in the field of titanium dioxide use in ceramics (Figure 28). Nevertheless, several leading industrial actors are also among the top players, suggesting the maturity of this area and its extended industrial use. Patents are most frequently filed by single applicants, although there are some collaborations between Chinese universities and companies.

Figure 26. Patent families related to ceramics by jurisdiction of first priority.
China is the most frequent country of first priority, followed by Japan and the Republic of Korea.

Source: WIPO, based on patent data from Orbit up to April 2022.

Figure 27. Patent families related to ceramics by jurisdiction, where at least one family member is granted.
Most patents are granted in China, followed by Japan, the United States, the Republic of Korea and Europe.

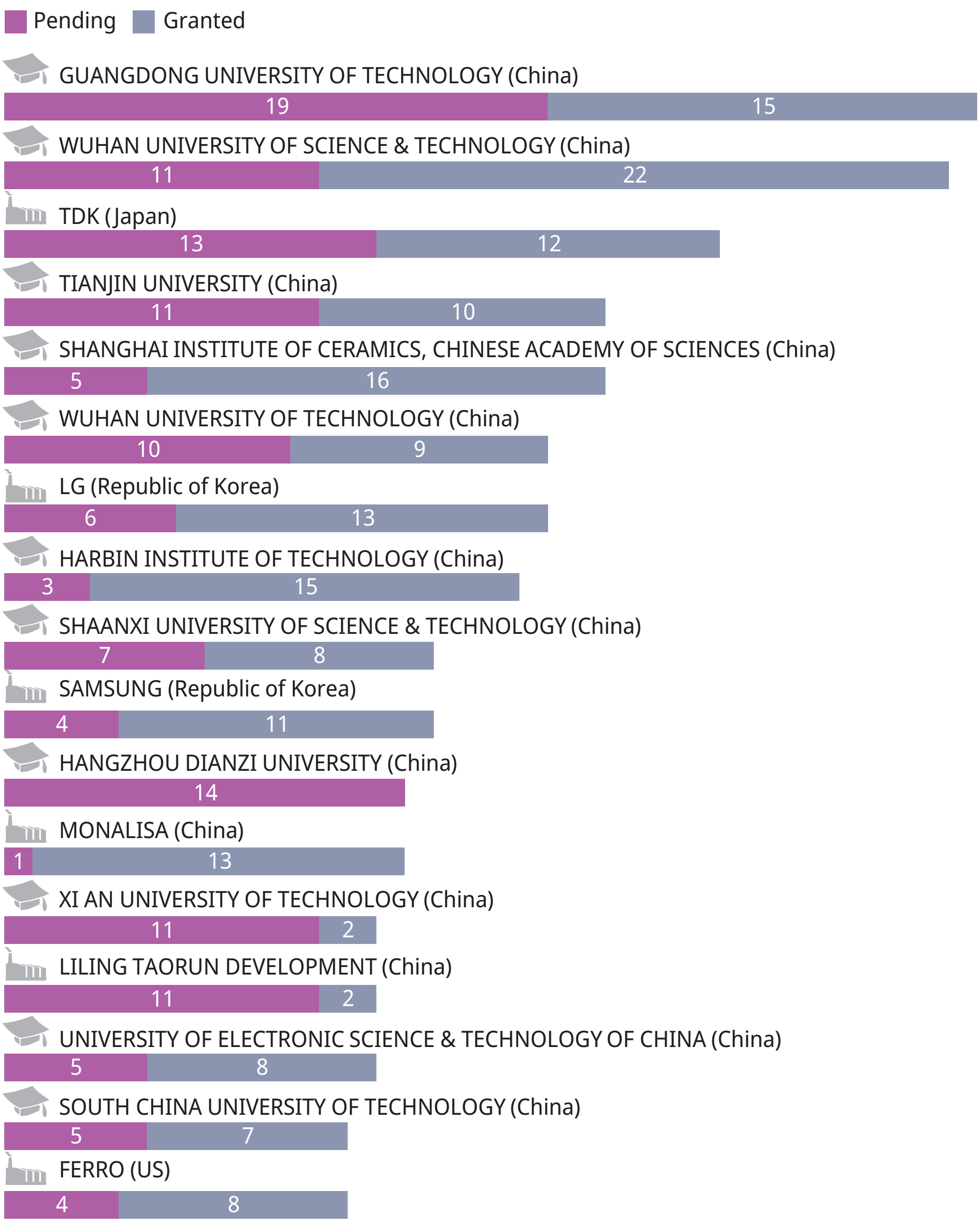
Note: Europe represents patent applications filed at the EPO.
Source: WIPO, based on patent data from Orbit up to April 2022.

Among the top six industrial players, three are multinational corporations and world leaders in electronic components and devices: namely, TDK (Japan), LG (Republic of Korea) and Samsung (Republic of Korea). Patents belonging to TDK and Samsung mainly protect titanium dioxide in ceramics used as insulating electronic components, while LG focuses on enamel compositions for oven coatings.

The other industrial key players are Monalisa and Liling Taorun Development, Chinese ceramic manufacturers of floor tiles, buildings and everyday applications, and Ferro, a ceramics manufacturer for automobiles, construction, consumer goods and electronics based in the United States.

The Guangdong University of Technology and the Wuhan University of Science and Technology are the main academic contributors. Wuhan University of Science and Technology has collaborated with the Jinzhou Guotai Industrial on five patent families related to materials having high heat resistance.

Figure 28. **Industrial and academic key players in the field of titanium use for ceramics.**
Key players include several Chinese universities and companies from Japan and the Republic of Korea.



Source: WIPO, based on patent data from Orbit up to April 2022.

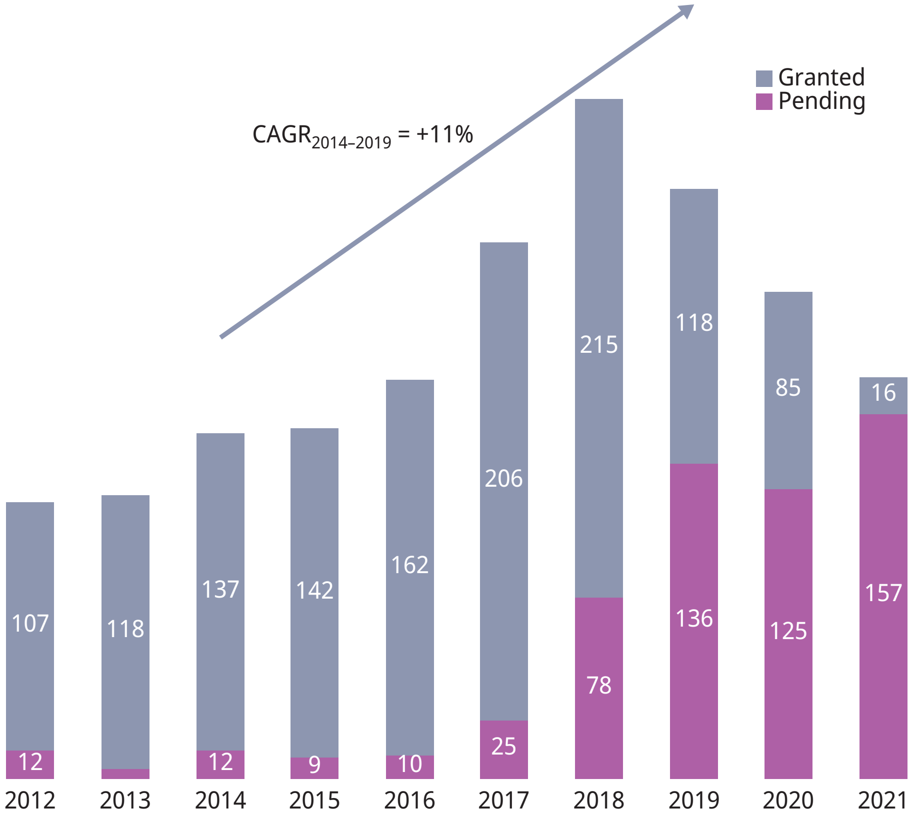
The patent activity of China, Japan and in the Republic of Korea reflects the important industrial role of these countries in the manufacturing of electronics, consumer goods and construction materials.

Electrodes for batteries

Patent activity

Between 2012 and 2022, there were 1,875 patent families filed that are still active and describe the application of titanium dioxide and titanium in electrodes for batteries. Patent activity has increased since 2012, with a CAGR of +11 percent between 2014 and 2019, which can be explained by the growing demand for electric cars (Figure 29).

Figure 29. Patent families related to titanium-based electrodes and batteries based on first priority year, 2012–2021.
Patent activity related to the use of titanium and titanium dioxide in electrodes for batteries has increased since 2012.



Note: CAGR is the compound annual growth rate. There is an average 18-month delay between patent filing and publication. 2019 is the last year for which complete data are available.

Source: WIPO, based on patent data from Orbit up to April 2022.

Patent content

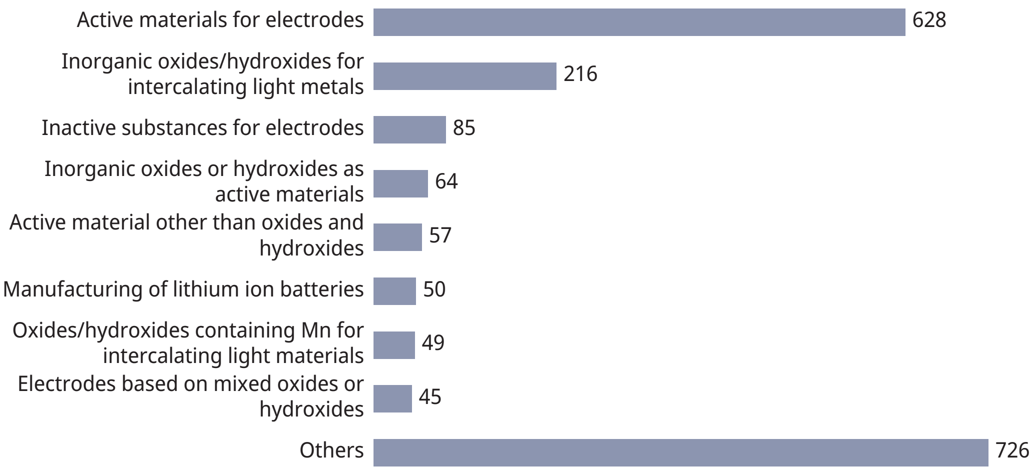
Patents in this area mainly describe the use of titanium dioxide and titanates as electrodes for batteries. Among the 1,875 patent families that are active, 808 mention terms related to nanotechnologies, such as nanoparticles, nanotubes, nanosheets and nanofibers, indicating the widespread use of nanosized compounds in electrodes for batteries.

Patent families in this section can be classified according to their principal IPC code, which reflects the chemical composition of the described products. The inventions are mainly divided into two categories: active compositions based on dioxides and hydroxides and compositions not based on dioxides and hydroxides (Figure 30).

Seventy-nine percent of patent families in this section mention lithium and 32 percent refer to compositions of lithium titanate. Lithium-titanate batteries may represent an improvement over

Figure 30. **Patents related to electrodes for batteries according to their chemical composition or special application.**

A significant proportion of patent families describe active materials for electrodes.



Source: WIPO, based on patent data from Orbit up to April 2022.

lithium iron phosphate batteries conventionally used in cars: they can endure more charging cycles, can be charged more rapidly and can work at higher temperatures without significant safety concerns (Changzhou Ruidefeng Precision Technology Co., Ltd., 2021).

Some inventions describe electrodes with catalytic activity, mainly to be used in fuel cells, while some other patents focus on electric conductors rather than electrodes; these two applications are included in the category "others" in Figure 30).

Geographical coverage and key players

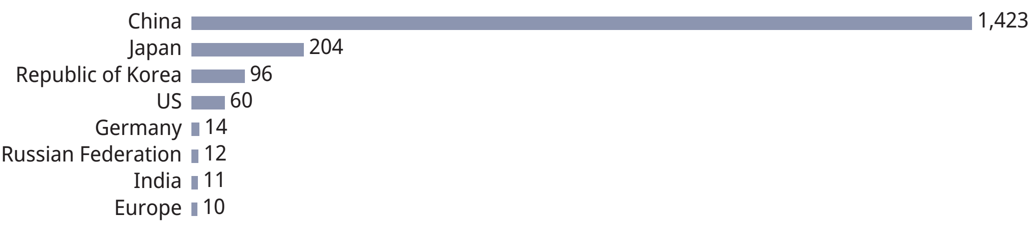
China is leading patent activity related to electrodes for batteries, with 76 percent of patent families having China as the first priority country (Figure 31). Chinese patent activity is markedly domestic, with 97 percent of Chinese inventions (corresponding to 74 percent of relevant patent families related to electrodes for batteries) being protected only in China.

Japan is second in terms of priority country, with 204 patent families related to electrodes, of which 61 percent are also protected in other countries. The Republic of Korea and the United States also emerge as first priority countries. Applicants filing in the United States as the first priority country have a high tendency to extend protection to other countries, with 76 percent of patent families also protected in other countries, compared to 50 percent for the Republic of Korea (Figure 32).

Patent filings related to the use of titanium in electrodes is led by both industrial actors and academic institutions (Figure 33). Although the top filer is an academic institution, Central South

Figure 31. **Patent families related to titanium-based electrodes and batteries by country of first priority.**

China is by far the most frequent first priority country for patents in the field of electrodes for batteries. Japan, the Republic of Korea and the United States are also important contributors.

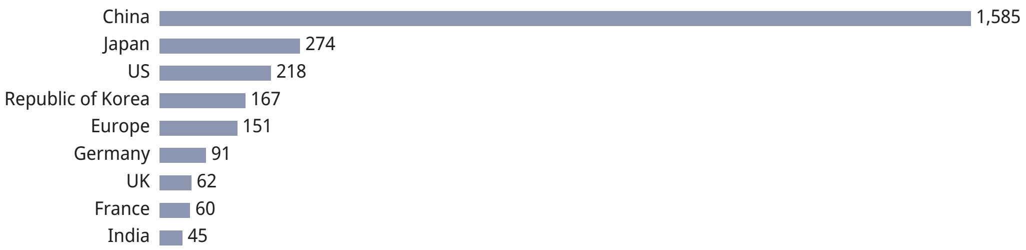


Note: Europe represents filings at the EPO.

Source: WIPO, based on patent data from Orbit up to April 2022.

Figure 32. **Patent families on titanium-based electrodes and batteries by jurisdiction, where at least one family member is granted.**

China has the largest number of active patents in the field of electrodes for batteries, significantly more that the countries that follow: namely, Japan, the United States, the Republic of Korea and Europe.

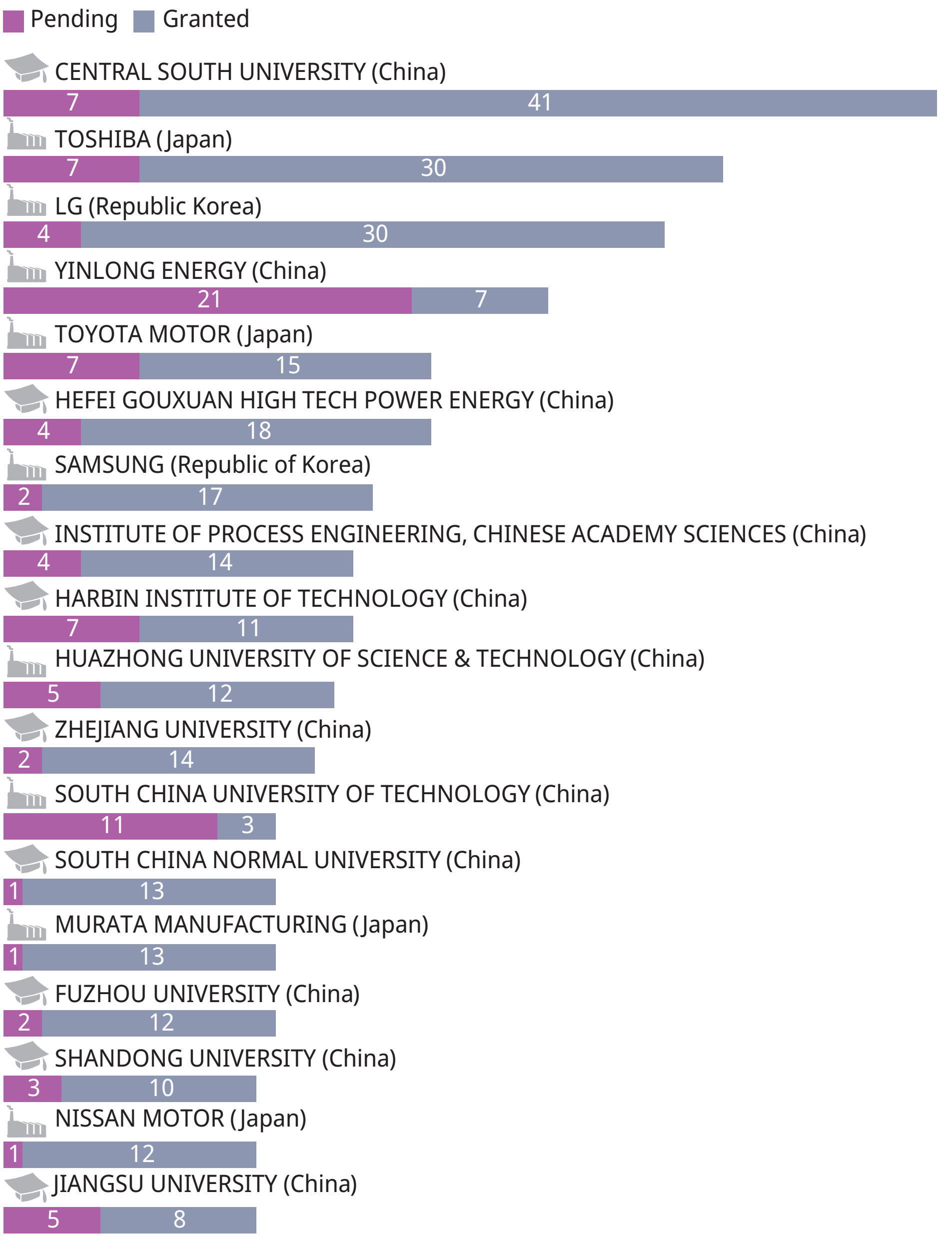


Note: Europe represents filings at the EPO.

Source: WIPO, based on patent data from Orbit up to April 2022.

Figure 33. **Industrial and academic key players in the field of titanium use for electrodes and batteries.**

Key players are almost exclusively Chinese companies, universities and public institutions.



Source: WIPO, based on patent data from Orbit up to April 2022.

University, the other players among the top five are companies. The presence of several large companies among the top actors shows the maturity of this technology and its broad industrial application. Most patents are filed by single applicants, although some collaboration between companies is present.

Several leading multinational companies from the electronics and automobile industries are among the top players. Their patents mainly focus on the use of titanium-based compounds as cathodes in lithium-based secondary batteries for electronics or automobiles. Among these key players, we find LG and Samsung Electronics, two leaders in electronics from the Republic of Korea, along with leading Japanese automobile manufacturers, Toshiba, Toyota and Nissan. The Japanese company Murata Manufacturing produces electronics components and has recently acquired Sony's battery business (Murata Manufacturing Co., Ltd., 2016). It has collaborated with the Canadian hydroelectric company Hydro Quebec on two patent families on electrolytes related to batteries.

Two Chinese companies specializing in the domain of batteries are also present among the key players. Yinlong Energy is one of the world leaders in lithium-titanate electrodes, and has acquired Otitan Nanotechnology, a US company with more than eight years of experience in this field, and the Chinese company Aotai Nanotechnology. Yinlong Energy and Aotai Nanotechnology co-own eight patent families related to lithium-titanate electrodes.

Another Chinese key player is Hefei Guoxuan, a Gotion High Tech subsidiary, which also produces batteries based on lithium-titanate electrodes.

The importance of China, Japan and the Republic of Korea in patent filing related to titanium-based electrodes reflects the prominent role of their electronics and automobiles industries.

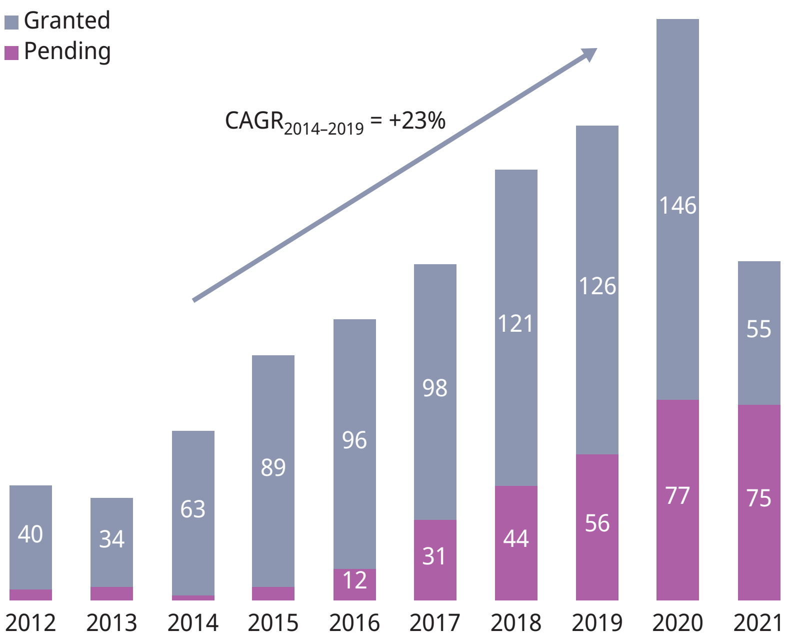
Medical technology

Patent activity

The set of results focusing on the use of titanium dioxide and titanium in the field of medical technology has 1,182 active patent families dating from 2012. Patent activity shows a growing interest in this field, with a CAGR of +23 percent between 2014 and 2019 (Figure 34).

Figure 34. **Number of patent families related to titanium use for medical devices based on first priority year, 2012–2021.**

Patent filing related to the use of titanium and titanium dioxide in medical technology has strongly increased since 2012.



Note: CAGR is the compound annual growth rate. There is an average 18-month delay between patent filing and publication. 2019 is the last year for which complete data are available.

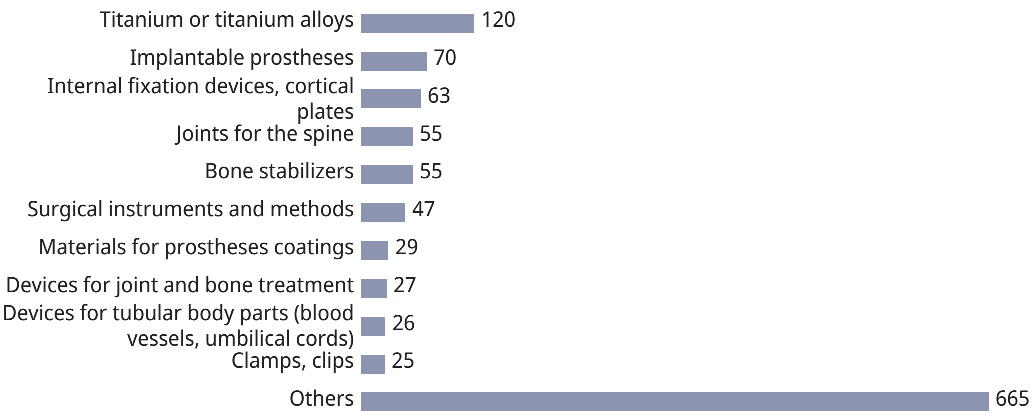
Source: WIPO, based on patent data from Orbit up to April 2022.

Patent content

Patents in the field of medical technology protect medical instrumentation made of titanium metal or titanium alloys, and their coatings, frequently based on titanium dioxide. Among the 1,182 active patent families in this field, only 162 mention terms related to nanotechnologies, indicating that the use of nanosized or nanostructured compounds in medical technology is very limited.

The classification of the inventions according to their principal IPC code reflects their specific application. Three types of products emerge: implantable products (bone prostheses, cortical plates, stents, clamps, spinal fixation, but also screws and suture material, included in "others" in Figure 35), non-implantable surgical instruments (guides, robots, but also surgical staplers, trocars and puncturing needles, included in "others" in Figure 35) and coatings for implantable devices (Figure 35). Implantable products are the most frequently described in patent applications. In these applications, titanium metal and titanium-containing alloys are used to exploit the high strength-to-weight ratio of titanium.

Figure 35. **Patent families on medical technology domain according to the specific product.**
The use of titanium and its alloys and implantable prosthetics are some key applications in the area.



Source: WIPO, based on patent data from Orbit up to April 2022.

Geographical coverage and key players

As is the case for other applications of titanium, China leads patent filing in the field of medical technology, with 79 percent of patent families having this as the country of first priority (Figure 36). As seen for the other application areas, Chinese patent activity is marked by domestic protection, with 96 percent of Chinese patent families (77 percent of the total relevant patent families) not protected in other countries. The Russian Federation is second in terms of priority filings with 99 patent families, of which 95 percent are protected only within the Russian Federation.

Among the various jurisdictions, China has the highest number of granted patents, followed by the Russian Federation, the United States and Europe (Figure 37).

Figure 36. **Number of patent families on titanium use for medical technology by jurisdiction of first priority.**
China is the most frequent first priority country and is followed by the Russian Federation.

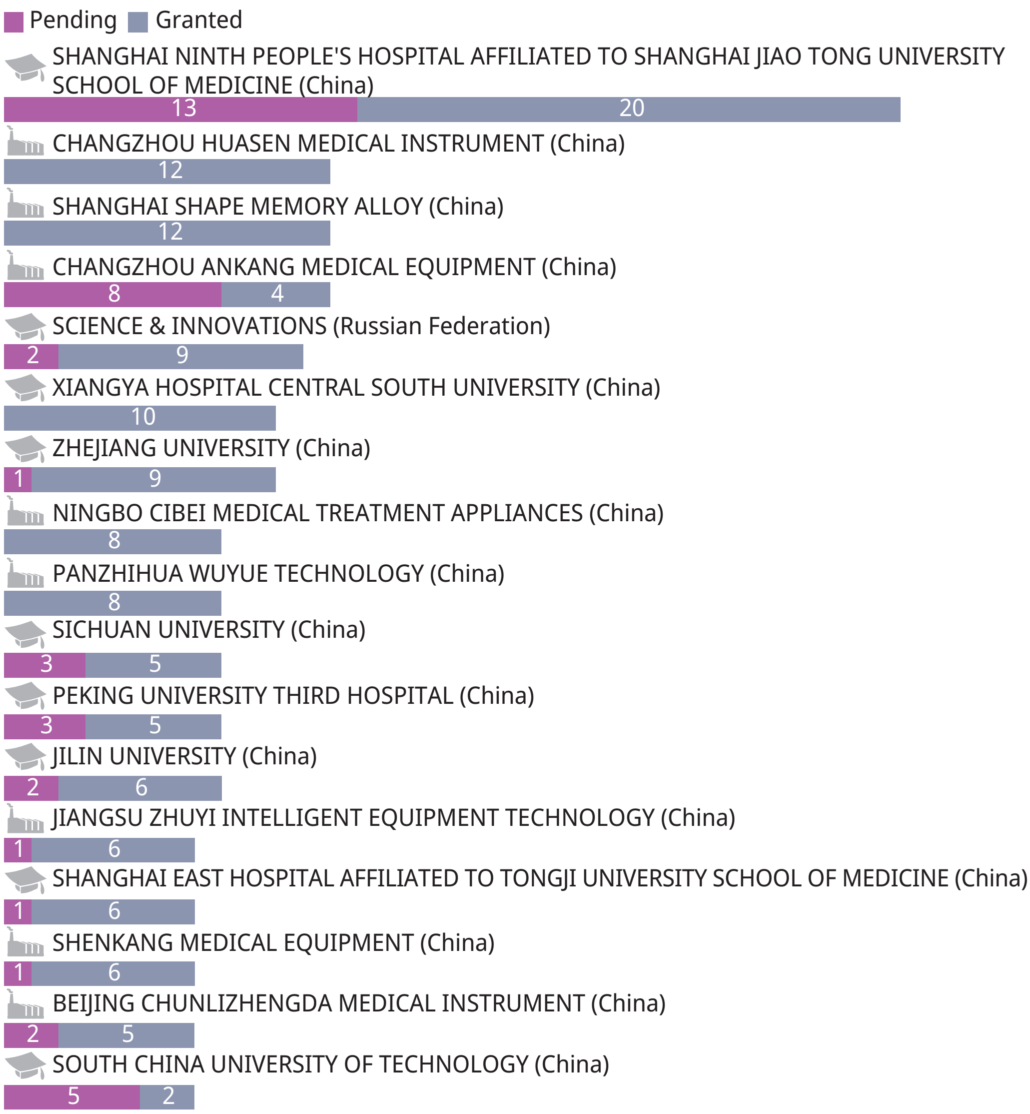
Source: WIPO, based on patent data from Orbit up to April 2022.

Figure 37. **Patent families on titanium use for medical technology by country where at least one family member is granted.**
China is the country with the highest number of granted patents. The Russian Federation, the United States and Europe (EPO) are also protected by a significant number of granted patents.

Note: Europe represents filings at the EPO.
Source: WIPO, based on patent data from Orbit up to April 2022.

Key players in the use of titanium in medical technology are almost exclusively Chinese companies, universities and hospitals, with the exception of a Russian state-owned institute (Figure 38). Patents are mainly filed by single applicants, apart from a collaboration between

Figure 38. **Industrial and academic key players in the field of titanium use for medical technology.**



Source: WIPO, based on patent data from Orbit up to April 2022.

Chinese universities. Shanghai Ninth People's Hospital Affiliated to Shanghai Jiao Tong University School of Medicine is the top player and leading research into titanium-based materials for bone fractures.

The presence of several Chinese companies among the key players indicates the widespread industrial development of this technological domain. Chinese companies can be divided into two groups:

- those working on surgical instruments or stents, which comprise Shanghai Shape Memory Alloy, Changzhou Ankang Medical Equipment, Shenkang Medical Equipment and Beijing Chunlizhengda Medical Instrument;
- those developing titanium-based materials for bone reconstruction such as implantable prostheses and their coatings, namely Panzhihua Wuyue Technology, Changzhou Huasen Medical Instrument and Ningbo Cibei Medical Treatment Appliances.

The South China University of Technology has collaborated with the Peking University Third Hospital on a patent describing a femoral implant based on a titanium alloy and coated with titanium dioxide.

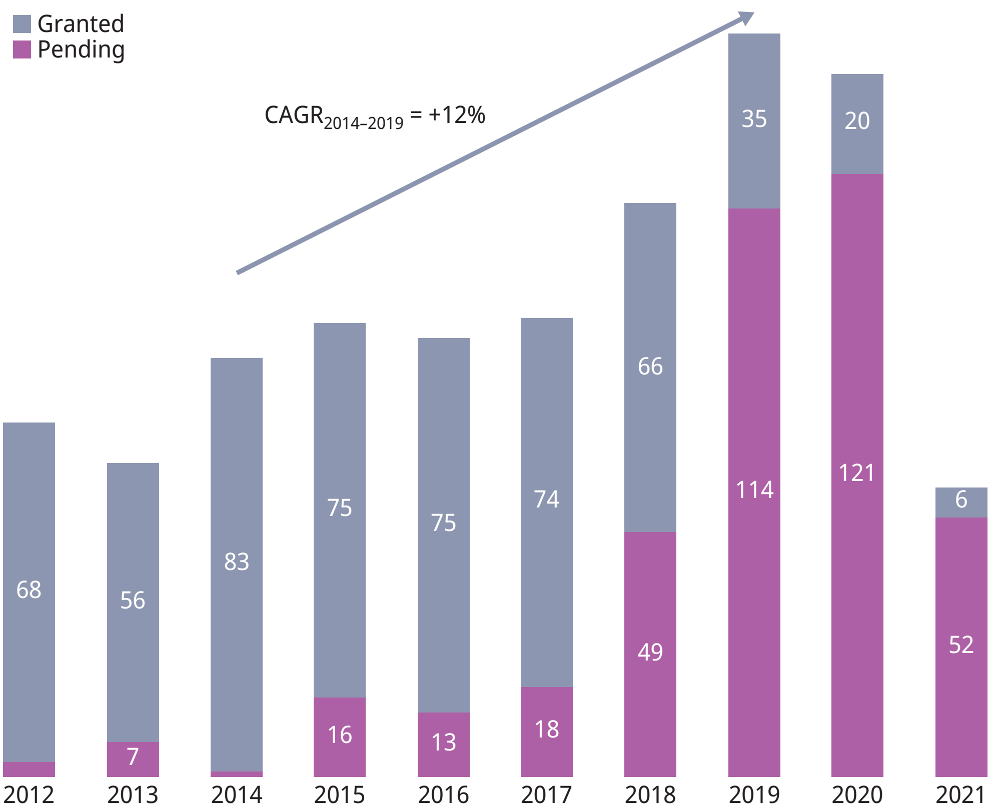
Non-Chinese actors do not feature among the top players, suggesting a lack of big companies specialized in this field outside of China.

Cosmetics

Patent activity

The set of results for patent families on the use of titanium dioxide and titanium in cosmetics contains 953 active patent families filed since 2012. Patent activity shows a small growth for this field during this period, with a CAGR of +12 percent between 2014 and 2019 (Figure 39).

Figure 39. **Number of patent families on titanium-based cosmetics, 2012–2021.**
Patent activity in the field of cosmetics has increased slightly since 2012.



Note: CAGR is the compound annual growth rate. There is an average 18-month delay between patent filing and publication. 2019 is the last year for which complete data are available.

Source: WIPO, based on patent data from Orbit up to April 2022.

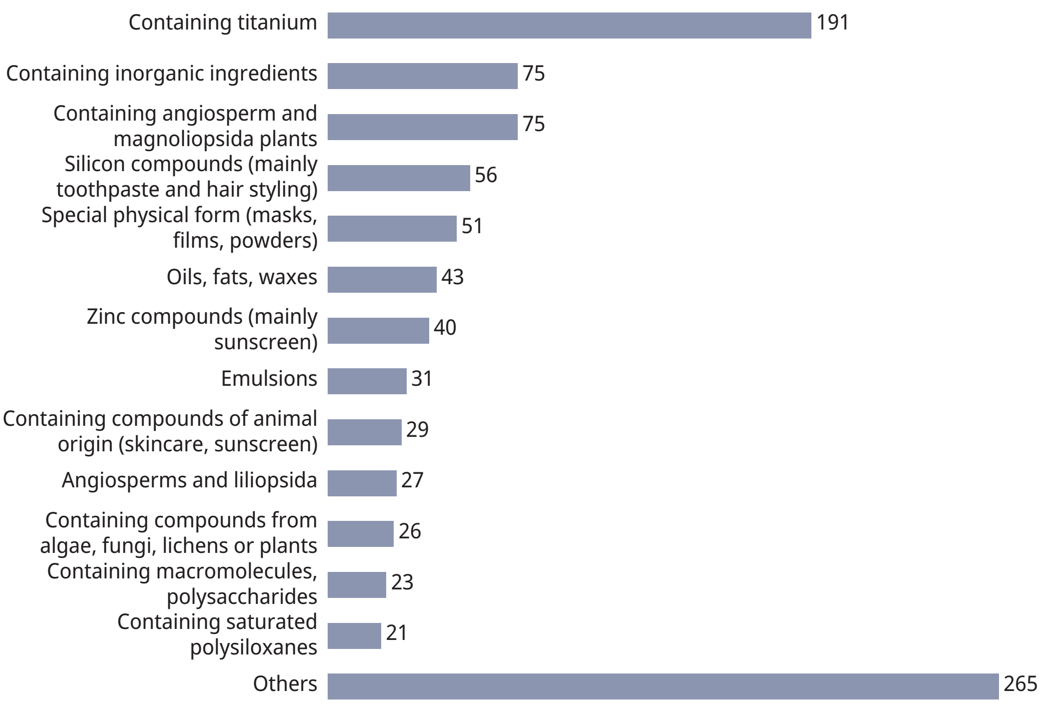
Patent content

Patents on the use of titanium and titanium dioxide in the field of cosmetics mainly cover products containing titanium dioxide for hair coloring/dressing, sunscreen, toothpaste, skin whitening and make-up for skin or lips. Titanium dioxide is used for its opacity and high covering power (an indication of how much material is needed to cover the previous color), as well as a UV filter.

Among the 953 active patent families in this field, only 167 mention terms related to nanotechnologies (nanoparticles, nanotitania), indicating that their use in cosmetics is quite limited. This is probably because titanium dioxide particles need to be larger than 100 nm to provide opacity and high covering power, and particles of this size are too large to fall into the definition of nanotechnology (European Union Scientific Committee on Consumer Safety, 2020).

The classification of patent families according to their principal IPC code might reflect the chemical composition of titanium-containing cosmetics (silicon compounds, zinc, specific flowers, compounds of animal or vegetal origin, polysaccharides, but also aluminum and heterocyclic compounds, included in “others” in Figure 40) or the physical form of the product (oils, waxes, emulsions, masks). Compositions containing angiosperm and magnoliopsida plants are mainly related to Chinese traditional medicine and used as toothpaste or as creams for skincare. Silicon-based cosmetics are mainly used as toothpaste or hair styling products. Zinc-based compositions pertain to sunscreen or skin-whitening products.

Figure 40. Patents in the cosmetics field according to their principal IPC code, reflecting their chemical composition.
Apart from titanium, cosmetic compositions include other chemical ingredients and products of plant or animal origin.



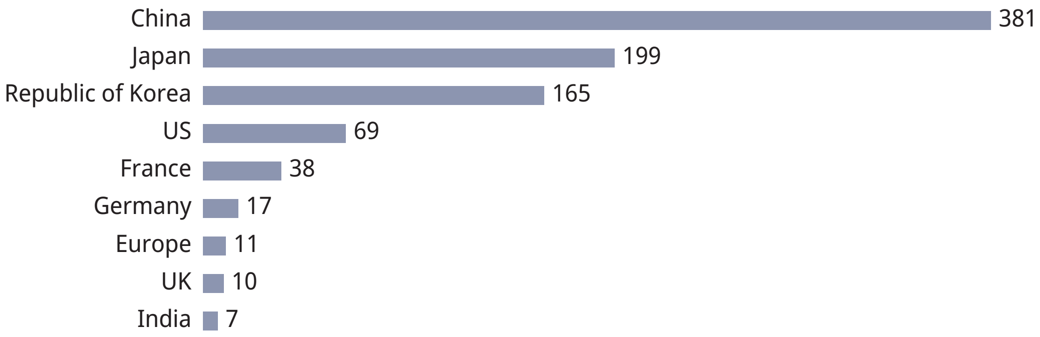
Source: WIPO, based on patent data from Orbit up to April 2022.

Geographical coverage and key players

Among the patent families in this application area, 87 percent had an Asian country as the country of first priority. China is the top country of priority filing, followed by Japan and the Republic of Korea (Figure 41).

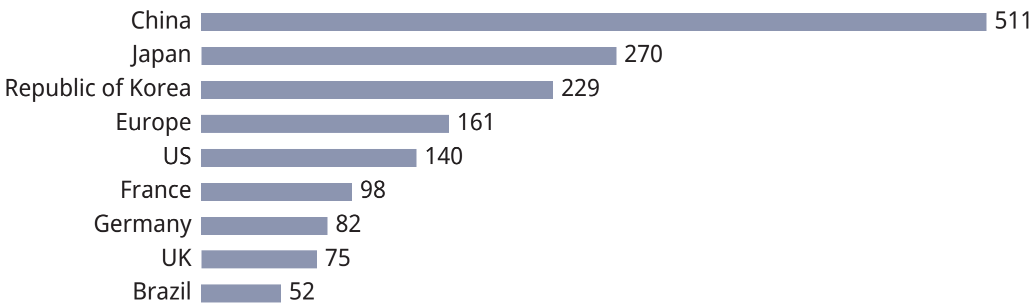
Although the United States and France are behind Asia in terms of filings, they have a tendency to protect their inventions in other countries also. Their main target jurisdictions for protection are Europe, China, Japan and the Republic of Korea.

Figure 41. **Patent families on titanium-based cosmetics by jurisdiction of first priority.**
China, Japan and the Republic of Korea are the most frequent jurisdictions of first priority filing.



Note: Europe represents filings at the EPO.
Source: WIPO, based on patent data from Orbit up to April 2022.

Figure 42. **Number of patent families related to titanium cosmetics by country, where at least one family member is granted.**
China, Japan and the Republic of Korea are the jurisdictions with most patents granted, followed by Europe and the United States.



Note: Europe represents filings at the EPO.
Source: WIPO, based on patent data from Orbit up to April 2022.

China, Japan and the Republic of Korea are the countries covered by the highest number of granted patents in this technological domain, although the United States and Europe are also protected by a significant number of patent families (Figure 42).

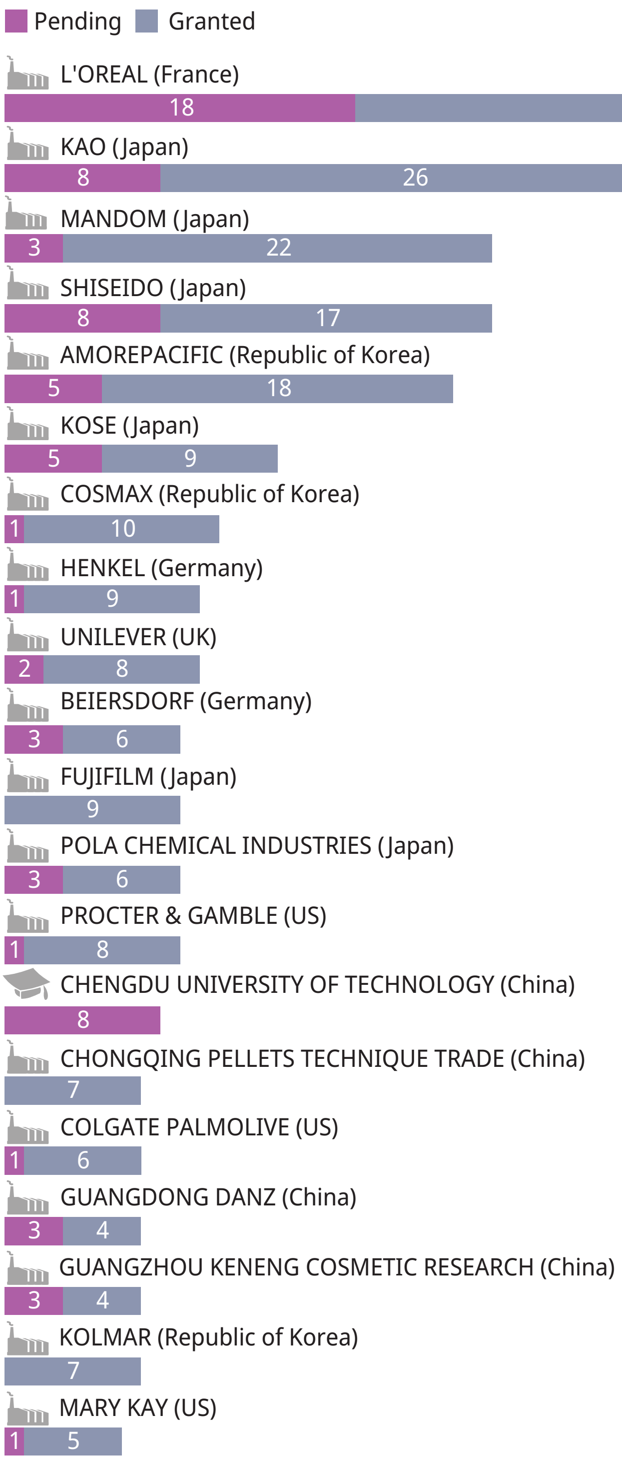
Patent protection on the use of titanium in cosmetics is more international and less strongly dominated by China, with only 39 percent of patent families covering only China (compared to between 74 and 80 percent for the other applications described in this report).

Key players regarding patents related to use of titanium-based materials in cosmetics are almost exclusively companies based in Japan, the United States, the Republic of Korea, France, Germany and China (Figure 43). Among the key players we found several big companies in the field of cosmetics and personal care. Single applicants file the majority of patents, although some companies and universities from the Republic of Korea have collaborated and filed applications jointly.

The dominance of large companies among the top actors reflects the widespread industrial use of titanium dioxide in cosmetics and the high maturity of this technology.

The French multinational company L'Oréal is the top player, with 53 active patent families and is followed by several Japanese cosmetic companies, such as Shiseido, Kao, Mandom, Kosé and Fujifilm. Mandom holds patents on hair structuring products and body deodorants.

Figure 43. **Industrial and academic key players in the field of titanium use for cosmetics.**
Key players are almost exclusively industries based in several different countries.



Source: WIPO, based on patent data from Orbit up to April 2022.

Amorepacific, Cosmax and Kolmar are cosmetic companies from the Republic of Korea, while Mary Kay is based in the United States. Cosmax and Kolmar have collaborated with Hanyang University: Cosmax co-owns a patent family on an infrared (IR)-blocking composition to prevent skin aging, while the collaboration of Kolmar relates to a patent family on a UV-blocking composition.

Unilever (UK) and Procter & Gamble (US) are leading companies in consumer goods and hold patents on titanium dioxide-containing products for skincare and make-up. Unilever and Colgate Palmolive (US) hold patents on the use of titanium dioxide in oral hygiene.

German companies Henkel and Beiersdorf are also key players: Henkel's patents focus on hair decolorization, while Beiersdorf has a patent family on sunscreen compositions containing titanium dioxide.

Guangzhou Keneg Cosmetic Research and Guangdong Danz are two Chinese cosmetic companies who collaborated with each other and with Guangzhou Baiyun Lianjia Fine Chemical Factory on seven patent families describing sunscreen and skin make-up compositions containing titanium dioxide.

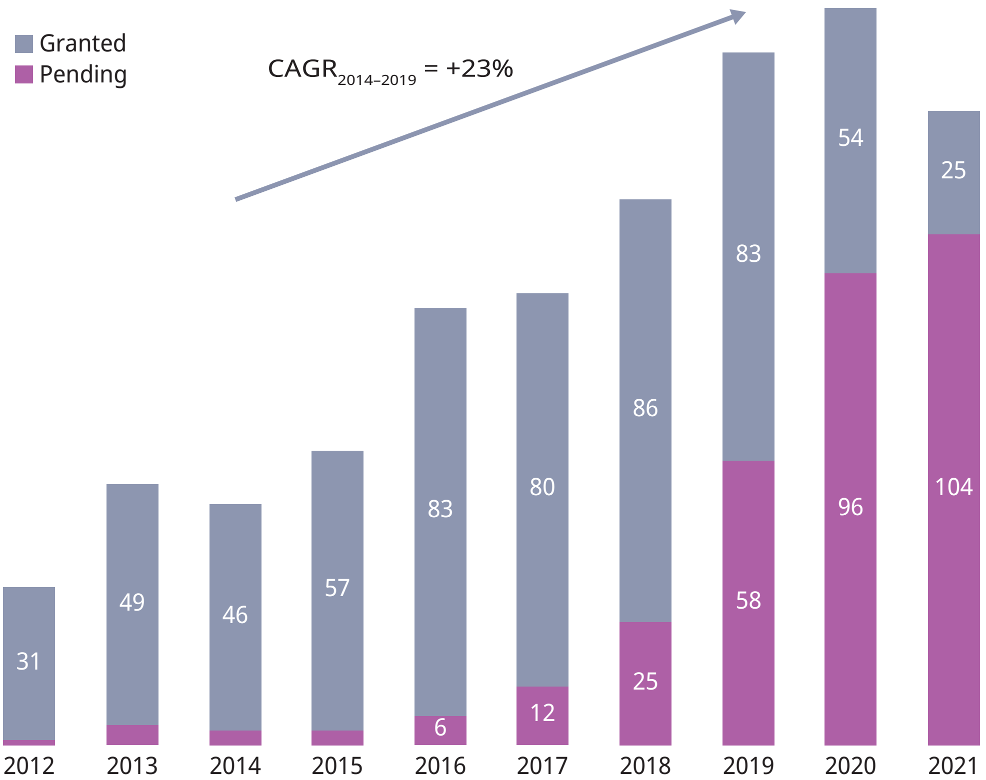
Although the number of its patents is very high, China is not well represented among the top players, because Chinese actors hold smaller portfolios.

Coatings

Patent activity

We found 908 patent families active since 2012 describing the use of titanium dioxide and titanium as a coating material. Patent activity shows a growing interest in titanium-based coatings, with a CAGR of +23 percent between 2014 and 2019 (Figure 44).

Figure 44. Number of patent families related to titanium-based coatings based on first priority year, 2012–2021.
The number of patent families related to titanium-containing coatings has strongly increased since 2012.

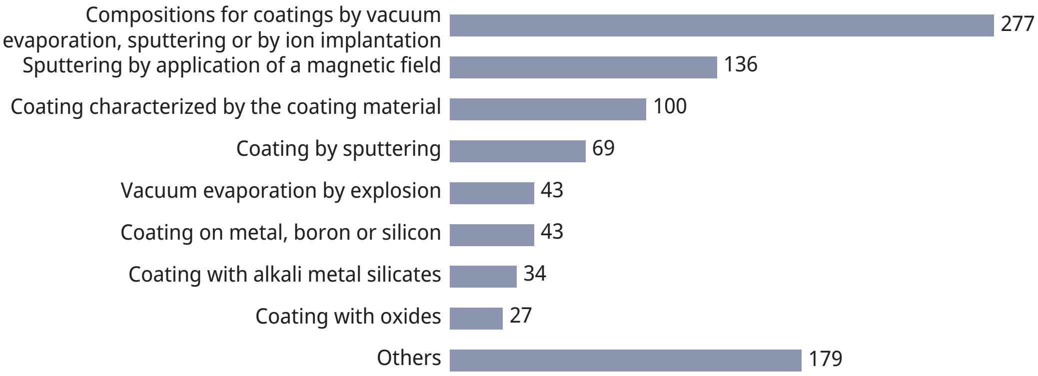


Note: CAGR is the compound annual growth rate. There is an average 18-month delay between patent filing and publication. 2019 is the last year for which complete data are available.
Source: WIPO, based on patent data from Orbit up to April 2022.

Patent content

Patents on the use of titanium compounds as a coating material mainly describe compositions with titanium dioxide and titanium alloys. Their principal IPC code reflects the specific coating techniques used (sputtering, but also vacuum evaporation and ion implantation and other specific techniques, included in "others" in Figure 45), the chemical composition of the coating (silicates, oxides) or the composition of the substrate (metal, boron, silicon) (Figure 45). The most frequent property these coatings are used for is increased resistance to corrosion, but other functionalities are also described, such as increased heat resistance, flame-retardant properties or decreased friction.

Figure 45. **Patent families in the field of coatings according to their principal IPC code.** *Classification reflects the coating process, the coating compositions and substrates, with most patents filed in the area of fabricating coatings by vacuum evaporation.*



Source: WIPO, based on patent data from Orbit up to April 2022.

Among the 908 active patent families in this field, 299 mention terms related to nanotechnologies such as nanostructure, nanotube or nanolayer, indicating a significant use of nanostructured materials in coatings.

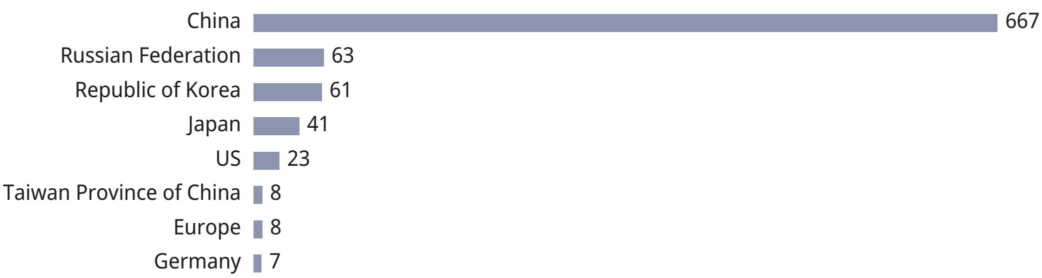
Geographical coverage and key players

Chinese applicants have led patent fillings, with 73 percent of patent families since 2012 (Figure 46). Chinese patenting activity is marked by a strong preference for domestic protection, with 72 percent of all relevant patent families protected only in China. The Russian Federation and the Republic of Korea also emerge as countries of first priority applications, although they are far behind China.

China is also the jurisdiction where the highest number of patent families (78 percent) has a granted patent (Figure 47). The Republic of Korea, the Russian Federation, Japan, the United States and Europe (EPO) are also protected by a significant number of granted patents.

The technological field of titanium-based coatings is dominated by academic players, mainly Chinese universities (Figure 48). Patents are filed by single applicants and no collaborations emerge between the top players. Two Russian universities are also present among the top players: the UFA State Aviation Technical University and the Ulyanovsk State Technical University. Their main focus is on coatings for aeronautics and metal cutting tools.

Figure 46. **Patent families on titanium coatings by jurisdiction of first priority.** *China is the most frequent country of priority and is followed by the Russian Federation and the Republic of Korea.*

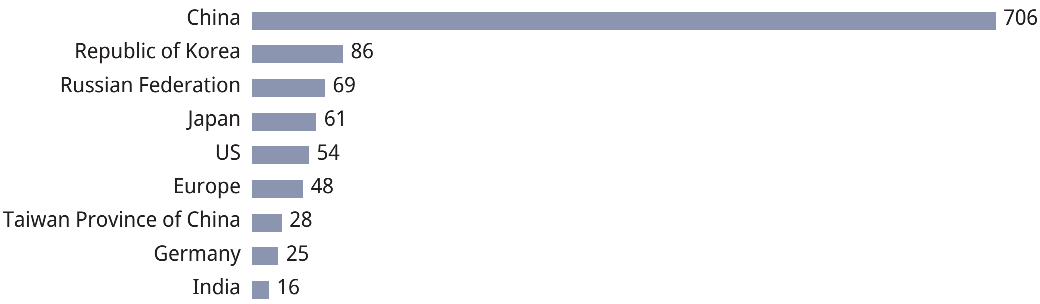


Note: Europe represents filings at the EPO.

Source: WIPO, based on patent data from Orbit up to April 2022.

Figure 47. **Patent families on titanium coatings by jurisdiction where at least one family member is granted.**

China has the highest number of granted patents, followed by the Republic of Korea, the Russian Federation, Japan, the United States and Europe.

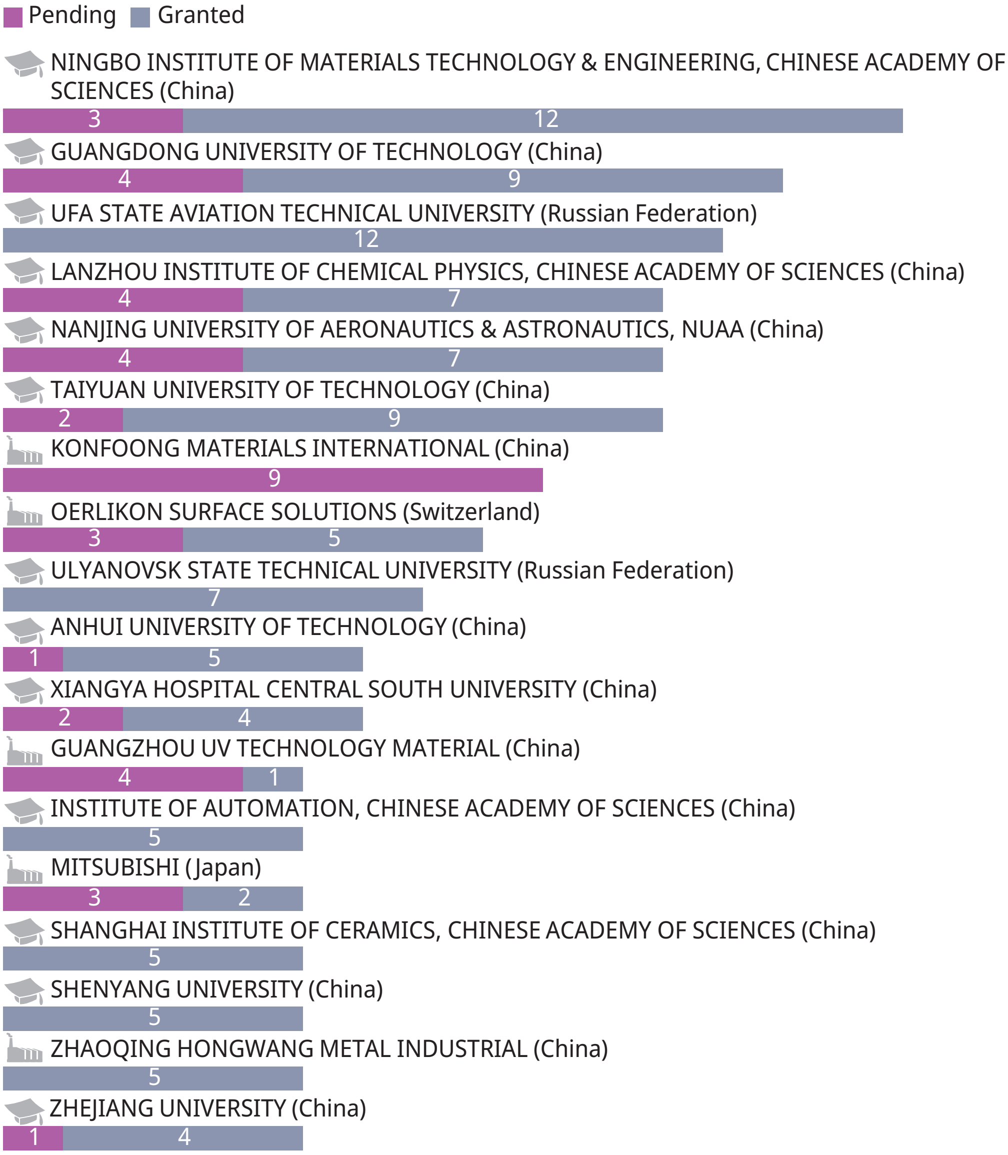


Note: Europe represents filings at the EPO.

Source: WIPO, based on patent data from Orbit up to April 2022.

Figure 48. **Academic and industrial key players in the field of titanium coatings.**

Key players are dominated by Chinese universities, although they include some industries.



Source: WIPO, based on patent data from Orbit up to April 2022.

Among industrial players, three Chinese companies are present: Konfoong Materials International specializes in manufacturing ultra-high-purity metal materials and coating materials for the semiconductor and integrated circuit industries; Guangzhou UV Technology Material is a leader manufacturer in coating materials for glass, photovoltaics, web and decorative products; Zhaoqing Hongwang Metal Industrial is a steel manufacturer.

Among non-Chinese industrial key players, we find Oerlikon Surface Solutions, a Swiss company that specializes in surface technology and coating solutions. Its patents focus on coatings for steel, ceramics and special anti-corrosion coatings. The Japanese corporation Mitsubishi owns five patent families related to coatings for heat exchangers, piezo-electric coatings and cutting tools.

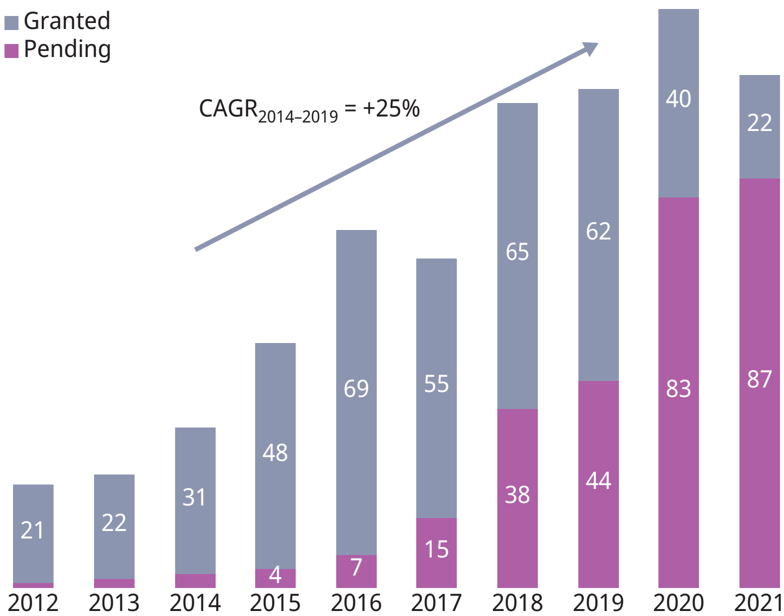
No key player is seen from the Republic of Korea in this category, although this country is important in terms of first priority filing.

Water treatment

Patent activity

The set of results for patent families regarding titanium dioxide and titanium used in the field of water treatment contains 719 active families. Patent activity shows an increasing interest since 2012, with a CAGR of +25 percent between 2014 and 2019 (Figure 49). Although the number of patents is limited, this technology is rapidly emerging and expected to further grow over the next few years.

Figure 49. Patent families related to titanium use in water treatment, 2012–2021.
The number of patent families related to the use of titanium and titanium dioxide in water treatment has increased strongly since 2012.



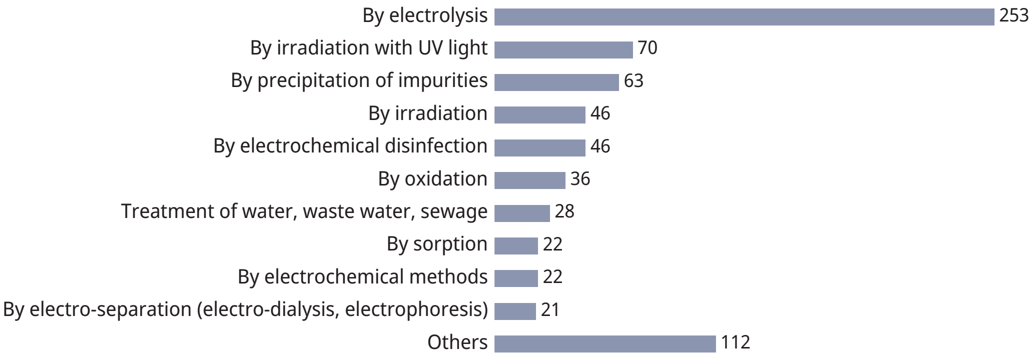
Note: CAGR is the compound annual growth rate. There is an average 18-month delay between patent filing and publication. 2019 is the last year for which complete data are available.

Source: WIPO, based on patent data from Orbit up to April 2022.

Patent content

Patents on the use of titanium in the field of water treatment can be classified according to the process used for the purification of water or wastewater (Figure 50). The majority of patent families describe electrolysis or electrochemical processes, where titanium dioxide or titanium composites are used as electrodes. Other patents describe a purification process by employing UV irradiation with titanium dioxide used as a photocatalyst. Another purification technique is based on flocculation and the precipitation of impurities and is mainly mediated by using titanium tetrachloride as a coagulant.

Figure 50. **Classification of patent families in the field of water treatment according to their principal IPC code, reflecting the water treatment process.**
Patents in this area are dominated by electrolysis processes, with a mixture of other technologies also being patented.



Source: WIPO, based on patent data from Orbit up to April 2022.

Among the 719 active patent families in this field, 219 mention terms related to nanotechnologies, such as nanotubes, nano-electrodes or nanoparticles, indicating a significant use of compounds of a nanometric size in water treatment.

Geographical coverage and key players

Chinese applicants lead patent fillings, with 89 percent of patent families since 2012 having China as the first priority country. Applications were also filed by players from the Republic of Korea, the Russian Federation, India and the United States, although far behind Chinese players in numbers (Figure 51).

China has also by far the highest number of granted patents in this field (Figure 52): 89 percent of patent families are protected in China, and 87 percent protected exclusively in China and not filed internationally.

Figure 51. **Number of patent families related to titanium use for water treatment by jurisdiction of first priority.**
China is by far the most frequent country of first priority, and is followed by the Republic of Korea.

Source: WIPO, based on patent data from Orbit up to April 2022.

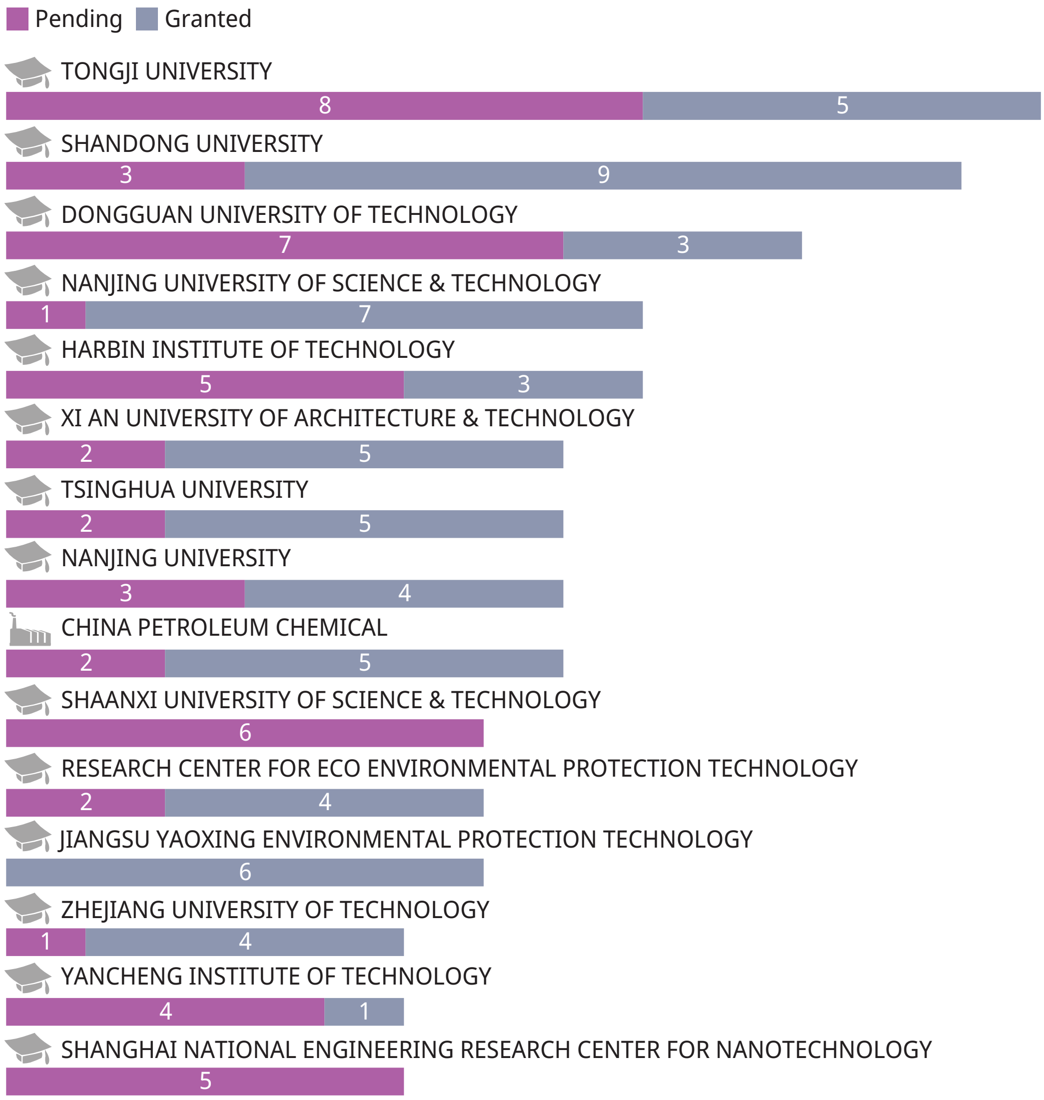
Figure 52. **Number of patent families related to titanium use for water treatment by country, where at least one family member is granted.**
As in other applications, China again has the highest number of granted patents.

Note: Europe represents filings at the EPO.
Source: WIPO, based on patent data from Orbit up to April 2022.

Chinese universities and public research institutes are leading patent filings related to the use of titanium and titanium dioxide for water treatment (Figure 53). China Petroleum Chemical is the only industrial key player. Patents are filed by single applicants and no collaboration between the top players emerge. The lack of other industrial contributors reflects the low maturity of this technology and its very recent emergence and high growth potential.

China Petroleum Chemical and Chinese public research institutes hold patents related to the use of titanium in the production of substrates, electrodes and molecular sieves for the electrocatalytic treatment of wastewaters.

Figure 53. **Industrial and academic key players in the field of titanium use for water treatment.**
Key players are mainly Chinese universities and public institutions.



Note: All key players in this graph are Chinese.
Source: WIPO, based on patent data from Orbit up to April 2022.

Perspectives

This report provides an overview of patent documents published until April 2022 related to the extraction of titanium dioxide and titanium metal from ilmenite mineral. It also includes a section on selected industrial applications of titanium-based compounds.

Since 2002, patent activity with regard to the process of obtaining titanium dioxide from ilmenite has grown strongly. Key contributors to patents on the production of titanium dioxide are companies from China, Australia and the United States, reflecting the major contribution of these countries to the industrial production of titanium dioxide.

Some patents describe pre-treatment processes to increase titanium concentration in low-grade ores and obtain titanium concentrates or slags. Other patents describe processes to obtain titanium dioxide, either by a direct hydrometallurgical process or through two industrially exploited processes, the sulfate and chloride processes.

The chloride process is described in very few patents, although it remains the most exploited process in the industrial production of titanium dioxide today. Given the findings in this patent landscape, we can expect the chloride process to be progressively substituted by more direct hydrometallurgical processes in future, which require fewer steps and are more convenient.

In contrast, patent activity related to the process for the production of titanium metal has remained steady since 2002. Key players in this field are mainly Japanese companies. All industrial key players describe the industrially exploited Kroll process, which is based on the reduction of titanium dioxide or titanium tetrachloride with magnesium.

Given the slow patent dynamic and the fact that a large majority of patents describe the Kroll process, we do not expect a big shift away from this process over the coming years. The only emerging technology seems to be molten salt electrolysis developed by the Chinese company Pangang.

A large and increasing number of patents filed since 2012 describe the use of titanium dioxide in ceramic insulators in electronics and as electrodes in batteries for electronic devices and automobiles. Key players in these fields are several multinational corporations in electronics and automobiles from Japan, the Republic of Korea and several Chinese universities. The presence of many leading industrial actors reflects the maturity of these technologies and their extended industrial use.

Titanium metal and titanium dioxide are also widely used in medical technology, and patent activity in this field is increasing strongly. Patents describe implantable medical devices and surgical instruments made of titanium metal or alloys, and their coatings made of titanium dioxide. This technological field is dominated by Chinese companies and universities.

Titanium dioxide is also widely used in cosmetic compositions for skincare, make-up and oral care. Key players in this field are almost exclusively companies coming from several countries in Asia, Europe and the United States. The significant presence of big companies among the top actors reflects the high maturity of this technology.

Other emerging applications of titanium dioxide are in the fields of coatings and water treatment. Titanium-based coatings mainly prevent the corrosion of metal. Key players in this field are companies and universities from China.

Patents in the field of water treatment describe the use of titanium dioxide or titanium composites as electrodes, photocatalysts, coagulants or in purification by UV irradiation, where titanium dioxide is used as a photocatalyst. This field is dominated by Chinese universities and the lack of industrial contributors reflects the low maturity of this technology and its growth potential.

Annex

Methodology and search strategy

Production of titanium dioxide

Scope definition

This section focuses on patents describing processes to obtain titanium dioxide from ilmenite ore. These processes comprise multiple steps; patents describing only intermediate steps were also included in the scope, for example:

- smelting or redox treatments to increase titanium content and obtain titaniferous slags or synthetic rutile;
- processes to obtain titanium tetrachloride or titanyl sulfate as intermediate products of the chloride and sulfate processes;
- processes to transform synthetic rutile into titanium dioxide.

Processes to obtain titanium dioxide from natural rutile or titano-magnetite were not specifically searched in the queries but were considered relevant.

Patents that were considered out of scope include:

- processes to separate ilmenite and titaniferous ores from other minerals;
- processes to recover titanium dioxide or titanium from wastewaters (e.g., catalyst recycling);
- reactors, devices and apparatus without process description;
- re-processing of titanium dioxide;
- analytical methods to measure specific process parameters.

Geographical and temporal coverage

The patents dataset has worldwide geographical coverage, because of the widespread production of titanium. The dataset covers patent families with an earliest priority date from 2002 to 2022. Because of the 18-month delay between patent filing and publication, the dataset built by April 15, 2022 is incomplete for 2020, 2021 and 2022.

Search query and dataset construction

The dataset for titanium dioxide extraction from ilmenite ores was built by searching for methods to produce titanium dioxide from ilmenite, titaniferous ores, titaniferous slags or synthetic rutile (query 1), and for methods to produce synthetic rutile intermediate product from ilmenite, titaniferous ores or titaniferous slags (query 2) (Table 1).

Table 1. Search queries used to build dataset for titanium dioxide production from ilmenite.

#	Query	Number of patent families
1	(((ILMENITE OR TITANIFEROUS) AND (TITANIUM OR TITANIA OR TITANATE OR TIO2 OR (SYNTHETIC RUTILE) OR (ARTIFICIAL RUTILE)))/TI/AB/CLMS/OBJ/ICLM) AND EPRD >= 2002	2,119
2	(((ILMENITE OR TITANIFEROUS OR (SYNTHETIC RUTILE) OR (ARTIFICIAL RUTILE)) AND (TITANIUM OR TITANIA OR TITANATE OR TIO2))/TI/AB/CLMS/OBJ/ICLM) AND EPRD >= 2002	2,229
3	1 OR 2	2,235

Note: There is an average 18-month delay between patent filing and publication. 2019 is the last year for which complete data are available.

Source: WIPO, based on patent data from Orbit up to April 2022.

The dataset set was manually reviewed to assess to relevancy of each patent family according to the scope definition.

Patent categorization

Patent families considered relevant to the scope were categorized for in-depth analysis. This was done according to keyword searches in title/abstract/claims and manual review.

Patent families were categorized according the following segmentation:

- *Titanium source*: ilmenite, rutile (synthetic or natural), titano-magnetite, ore/slag/tailing, not specified.
- *Processing*: smelting, redox treatment, magnetic separation, sulfate, chloride, Becher, acid leaching, alkaline leaching, fluorine, microwave irradiation, electrolysis, bioleaching, other.

Production of titanium metal

Scope definition

This section focuses on patents describing processes to obtain titanium metal from ilmenite, rutile, titaniferous ores and titaniferous slags. Processes to obtain titanium metal from intermediate products such as synthetic rutile, titanium dioxide or titanium tetrachloride were not specifically searched in the queries but considered relevant.

Geographical and temporal coverage

The patent dataset has worldwide geographical coverage, because of the widespread production of titanium. The dataset covers patent families with an earliest priority date from 2002 to 2022. Because of the 18-month delay between patent filing and publication, the dataset built by April 15, 2022 is incomplete for 2020, 2021 and 2022.

Search query and dataset construction

The dataset for titanium dioxide extraction from ilmenite ores was built by searching for methods to produce titanium metal or sponge from ilmenite, titaniferous ores, titaniferous slags or synthetic rutile (query 1), and searching for the two industrially used processes (query 2) (Table 2).

The dataset set was manually reviewed to assess to relevancy of each patent family according to the scope definition.

Table 2. Search queries used to build dataset for titanium metal production from ilmenite.

#	Query	Number of patent families
1	(((ILMENITE OR TITANIFEROUS SLAG? OR TITANIFEROUS ORE? OR RUTILE OR (FURNACE 1D SLAG?)) AND ((TITANIUM D METAL) OR (SPONGE D TITANIUM) OR METALLIC TITANIUM))/TI/AB/CLMS/OBJ/ICLM) AND EPRD >= 2002	260
2	(((HUNTER PROCESS OR KROLL PROCESS))/TI/AB/CLMS/OBJ/ICLM) AND EPRD >= 2002	45
3	1 OR 2	304

Note: There is an average 18-month delay between patent filing and publication. 2019 is the last year for which complete data are available.

Source: WIPO, based on patent data from Orbit up to April 2022.

Patent categorization

Patent families considered relevant to the scope were categorized for in-depth analysis. This was done according to keyword searches in title/abstract/claims and manual review.

Patent families were categorized according to the following segmentation:

- *Titanium source*: ilmenite, rutile (synthetic or natural), titano-magnetite, titaniferous ore/slag/tailing, not specified/other.

- *Reducing agent*: magnesium (Kroll process), sodium (Hunter and Armstrong processes), aluminum, calcium, carbon/carbon-based, manganese, vanadium, other metal, electrolysis, hydrogen, plasma, not specified.
- *Titanium product*: sponge, powder/particles, ingot/rod/billet, not specified.

Industrial applications of titanium dioxide and titanium

Scope definition

This section is dedicated to a macroscopic analysis of patents describing industrial applications of titanium dioxide, titanium metal and titanium alloys. All types of titanium-containing materials were considered and patents collected in all industrial domains. For the analysis, some specific application domains were selected, focusing more on high-tech applications.

Geographical and temporal coverage

The patent dataset has worldwide geographical coverage and covers patent families with an earliest priority date from 2012 to 2022. The temporal coverage is restricted to this period to focus on the most recent applications and to estimate emerging trends in the next few years. Because of the 18-month delay between patent filing and publication, the dataset built by April 15, 2022 is incomplete for 2020, 2021 and 2022.

Search query and dataset construction

The dataset was built by searching for uses, applications, products or compositions of titanium dioxide or titanium (Table 3). Patents corresponding to chemical and physical processes and related apparatus were excluded by use of the B01 CPC classification. In addition, only granted or pending patents were considered.

Table 3. Search queries used to build dataset for titanium dioxide production from ilmenite.

#	Query	Number of patent families
1	((((TITANIUM OR TITANIA OR TITANATE OR TIO2) P (USE? OR APPLICATION? OR PRODUCT? OR HIGH_TECH OR COMPOSITION?)/TI/AB/ICLM) AND EPRD >= 2012) NOT (B01+)/IPC/CPC) AND (STATE/ACT=ALIVE)	53,754

Note: There is an average 18-month delay between patent filing and publication. 2019 is the last year for which complete data are available.

Source: WIPO, based on patent data from Orbit up to April 2022.

Selection of application domains for analysis

The patent dataset was divided into different pools according to the technology classification defined by WIPO crossed with the principal IPC of each patent. Among the 36 technology-IPC pool containing the largest number of documents, shown in Table 4, some specific pools were selected according to following criteria:

- the type of patent, focusing on products and excluding processes, analysis methods and general compositions without application;
- the “high-tech” character of the application domain, for example, considering paints and cements as low tech;
- the variation in the number of documents since 2012, to identify emerging technologies.

According to the selection criteria described above, six pools of patent families corresponding to high-tech applications were chosen for analysis (Table 5).

Table 4. **Pools of patent families according to technology and principal IPC, number of documents, temporal variation and pool selection.**

Technology	Principal IPC	Patent families	Δ(2017–2022)/ (2012–2016)	Selection focus
Materials, metallurgy	C04B-035 (ceramics)	1,683	+93%	CERAMICS
Electrical machinery, apparatus, energy	H01M-004 (electrodes)	1,564	+74%	ELECTRODES for BATTERIES
Materials, metallurgy	C01G-023 (titanium compounds)	1,318	+55%	Not selected
Organic fine chemistry	A61K-008 (cosmetics)	953	+40%	COSMETICS
Environmental technology	C02F-001 (water treatment)	719	+146%	WATER TREATMENT
Macromolecular chemistry, polymers	C08L-023 (polymer compositions)	653	+51%	Not selected
Materials, metallurgy	C22C-038 (ferrous alloys, steel)	640	+11%	Not selected
Surface technology, coating	C09D-133 (polymer coatings)	635	+49%	Not selected
Materials, metallurgy	C22C-014 (alloys based on titanium)	584	+44%	Not selected
Surface technology, coating	C23C-014 (coatings with special processes)	563	+103%	COATINGS
Medical technology	A61B-017 (surgical devices)	558	+201%	MEDICAL TECHNOLOGY
Basic material chemistry	C09D-163 (epoxy resins coatings)	533	+43%	Not selected
Materials, metallurgy	C22C-001 (making non-ferrous alloys)	528	+109%	Not selected
Materials, metallurgy	C03C-003 (glass compositions)	482	–12%	Not selected
Machine tools	B23K-035 (welding rods)	480	+50%	Not selected
Materials, metallurgy	C04B-028 (cements, concrete)	459	+140%	Not selected
Macromolecular chemistry, polymers	C08F-010 (polymers)	498	–45%	Not selected
Basic material chemistry	C09C-001 (dyes, paints)	421	+46%	Not selected
Materials, metallurgy	C22C-021 (aluminum-based alloys)	414	+42%	Not selected
Macromolecular chemistry, polymers	C08G-063 (polymers)	383	+7%	Not selected
Basic material chemistry	C09D-005 (coatings, paints)	378	+63%	Not selected
Basic material chemistry	C09D-175 (polymer coatings)	364	+80%	Not selected
Environmental technology	C02F-009 (water treatment)	362	+120%	Not selected
Measurement	G01N-027 (electric analysis)	351	+72%	Not selected
Macromolecular chemistry, polymers	C08L-027 (polymers)	350	45%	Not selected
Basic material chemistry	C09D-001 (coatings, paints)	345	+156%	COATINGS
Materials, metallurgy	C03C-008 (enamels, glazes)	344	+225%	CERAMICS
Surface technology, coating	C25D-011 (electrolytic coating)	343	+79%	Not selected
Materials, metallurgy	C22F-001 (alloys treatment)	326	+76%	Not selected
Surface technology, coating	B32B-027 (layered resins)	323	27%	Not selected
Materials, metallurgy	C22B-034 (obtaining refractory metals)	321	+141%	Not selected
Basic material chemistry	C09D-011 (inks)	319	–3%	Not selected
Medical technology	A61L-027 (prostheses)	317	48%	MEDICAL TECHNOLOGY
Electrical machinery, apparatus, energy	H01M-010 (secondary elements for electrochemistry)	311	17%	ELECTRODES for BATTERIES
Medical technology	A61F-002 (prostheses, stents)	307	+170%	MEDICAL TECHNOLOGY
Semiconductors	H01L-021 (processes to fabricate semi-conductors)	303	–23%	Not selected

Gray = negative growth; pink = up to 60% growth; purple = more than 60% growth.

Source: WIPO, based on patent data from Orbit up to April 2022.

Note: There is an average 18-month delay between patent filing and publication. 2019 is the last year for which complete data are available.

Table 5. **Selected pools of patent families, their technology and IPC classification, the number of patent and their temporal evolution.**

Pool	Principal IPC	Principal IPC	Patent families	Δ(2017–2022)/ (2012–2016)
CERAMICS	Materials, metallurgy	C04B-035 and C03C-008	2,027	+109%
ELECTRODES FOR BATTERIES	Electrical machinery, apparatus, energy	H01M-004 and H01M-010	1,875	+63%
MEDICAL TECHNOLOGY	Medical technology	A61B-017, A61L-027, A61F-002	1,182	+185%
COSMETICS	Organic fine chemistry	A61K-008	953	+40%
COATINGS	Surface technology, coating	C23C-014, C09D-001	908	+121%
WATER TREATMENT	Environmental technology	C02F-001	719	+146%

Pink = up to 60% growth; purple = more than 60% growth.

Note: There is an average 18-month delay between patent filing and publication. 2019 is the last year for which complete data are available.

Source: WIPO, based on patent data from Orbit up to April 2022.

Glossary

C	carbon
CAGR	The compound annual growth rate, or CAGR, is the average rate at which a value grows over a certain period of time (CAGR Calculator, n.d.). The formula for CAGR is: $CAGR = (EV/SV)^{1/n} - 1$, where EV = ending value; SV = starting value; *n* = number of years.
Cl_2	chlorine
CO	carbon monoxide
CO_2	carbon dioxide
Fe	iron
$FeSO_4$	iron sulfate
$FeTiO_3$	ilmenite
H_2SO_4	sulfuric acid
Mg	magnesium
$MgCl_2$	magnesium chloride
Na	sodium
NH_4Cl	ammonium chloride
O_2	oxygen
Patent	A legal title that gives inventors the right, for a limited period (usually 20 years), to prevent others from making, using or selling their invention without their permission in the countries for which the patent has been granted.
Patent application/filing	A request for patent protection for an invention in a given jurisdiction filed with a patent office.
Patent family	A set of interrelated patent applications filed in one or more countries to protect the same or a similar invention by a common inventor and linked by one or several common priority data. For this report's search and analysis, the FAMPAT family definition as used in Orbit Intelligence was used. A patent family is considered granted if at least one member patent has been granted, pending if no member patent has been granted and the grant decision for at least one member is pending, and lapsed if none of the patents in the family is active for any reason.
Priority	The earliest filing of the first patent in a family of patent applications, which includes a priority date and a priority country, that is the jurisdiction where it was first filed.
Ti	titanium
$TiCl_4$	titanium tetrachloride
TiO_2	titanium dioxide
$TiOSO_4$	titanyl sulfate

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WIPO
WORLD
INTELLECTUAL PROPERTY
ORGANIZATION

World Intellectual Property Organization
34, chemin des Colombettes
P.O. Box 18
CH-1211 Geneva 20
Switzerland

Tel: + 41 22 338 91 11
Fax: + 41 22 733 54 28

For contact details of WIPO's
External Offices visit:
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WIPO Publication No. 1077EN/23
ISBN: 978-92-805-3439-9 (print)
ISBN: 978-92-805-3438-2 (online)
ISSN: 2790-7007 (print)
ISSN: 2790-7015 (online)