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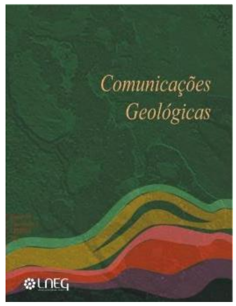
General review of titanium ores in exploitation: present status and forecast

Revisão geral dos minérios de titânio em exploração: estado atual e previsão



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Abstract: Titanium ore minerals have a unique spectrum of properties useful for modern-day industrial applications. This study focuses on the global distribution, genesis, processing, and economics of titanium ore minerals. Titanium ore deposits are distributed in 20 countries. Ilmenite ($FeOTiO_2$), leucoxene ($Fe_2O_3.nTiO_2$), and rutile (TiO_2) are the major Ti ores. Titanium ore minerals in rocks (*i.e*., primary deposits) are products of magmatic, hydrothermal, metasomatic, and metamorphic processes. Titanium ore minerals are also concentrated as unconsolidated/placer deposits (*i.e*., secondary deposits) due to weathering (chemical, physical and biological), erosion, and transportation of sediments. About 60% of global Ti ore production comes from unconsolidated mineral sand deposits. China is the leading producer of ilmenite accounting for 31% of global production, primarily from hard-rock deposits. Australia and South Africa are also leading producers of ilmenite. In addition, Australia leads rutile production with a global share of 52%. Titanium ore minerals are used to extract TiO_2 and Ti metal, using three major processes pyrometallurgy, hydrometallurgy, and electrometallurgy. Therefore, processed TiO_2 and Ti metal are used in advanced applications such as the production of paints, aircraft, photovoltaic cells, medicines, and biomedical engineering. Substitutions are virtually impossible in most applications of TiO_2 due to its unique physical and chemical properties. Time series analysis and forecast (using the R studio software) of global production and price variations of ilmenite and rutile indicate satisfactory growth rates, based on the United States Geological Survey (USGS) database and mineral yearbooks over 65 years from 1950 to 2015.

Keywords: Titanium ores, ilmenite, rutile, titanium dioxide, titanium metal.

Resumo: Os minérios de titânio têm um espectro único de propriedades úteis para as atuais aplicações industriais. Este estudo centra-se na distribuição global, génese, processamento e economia de minérios de titânio. Os depósitos de minério de titânio encontram-se distribuídos por 20 países. Ilmenite ($FeOTiO_2$), leucoxena ($Fe_2O_3.nTiO_2$) e rútilo (TiO_2) são os principais minérios de Ti. Os minérios de titânio em rochas (ou seja, depósitos primários) são produtos de processos magmáticos, hidrotermais, metassomáticos e metamórficos. Os minérios de titânio também ocorrem sob forma de concentrados em depósitos não consolidados/tipo *placer* (isto é, depósitos secundários) devido a alteração (química, física e biológica), erosão e transporte de sedimentos. Cerca de 60% da produção global de minério de Ti provém de depósitos de areia não consolidados. A China é o principal produtor de ilmenite, que representa 31% da produção global, principalmente a partir de depósitos de *hard-rock*. A Austrália e a África do Sul são também líderes mundiais na produção de ilmenite. Além disso, a Austrália lidera a produção de rútilo, com uma quota global de 52%. Os minerais de titânio são usados para extrair TiO_2 e o metal Ti, utilizando três grandes processos: pirometalurgia, hidrometalurgia e eletrometalurgia. Por isso, o TiO_2 processado e o metal Ti são utilizados em aplicações avançadas, como a produção de tintas, em aeronaves, células fotovoltaicas, medicamentos e engenharia biomédica. As substituições são virtualmente impossíveis na maioria das aplicações do TiO_2 devido às suas propriedades físicas e químicas únicas. A análise e previsão das séries temporais (utilizando o *software* R *studio*) da produção global e variações de preços de ilmenite e rútilo indicam taxas de crescimento satisfatórias, com base na base de dados do *United States Geological Survey* (USGS) e nos anuários minerais ao longo de 65 anos, de 1950 a 2015.

Palavras-chave: Minérios de titânio, ilmenite, rútilo, dióxido de titânio, metal de titânio.

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1. Introduction

The requirement for raw materials is ever increasing with industrialisation, technological advancement, and the move away from traditional energy generation. These raw materials are irreplaceable in photovoltaic cells, wind turbines, electric vehicles, and energy-efficient lighting (European Commission, 2022). In particular, most of these raw materials have been categorised as critical raw materials (CRMs) by various organisations such as the European Union (EU) (Girtan *et al*., 2021). Although the assessment of criticality varies, it mainly represents the economic significance and the supply risk over time. The list of critical raw materials for the EU is revised once every three years and the latest revision in 2020 also included titanium (Girtan *et al*., 2021). Titanium contributes to 0.6% of the Earth's crust (Das *et al*., 2013). A wide spectrum of minerals contains Ti, usually in the tetravalent state (Dill, 2010). For example, various minerals contain titanium oxides between 15 and 95%, and those with concentrations above 25% can be considered good sources for the extraction of Ti metal (Tab. 1). Ilmenite, leucoxene, and rutile are the major commercially interesting titanium dominant minerals (Fig. 1). TiO_2 and Ti metal are extracted/refined mainly from these

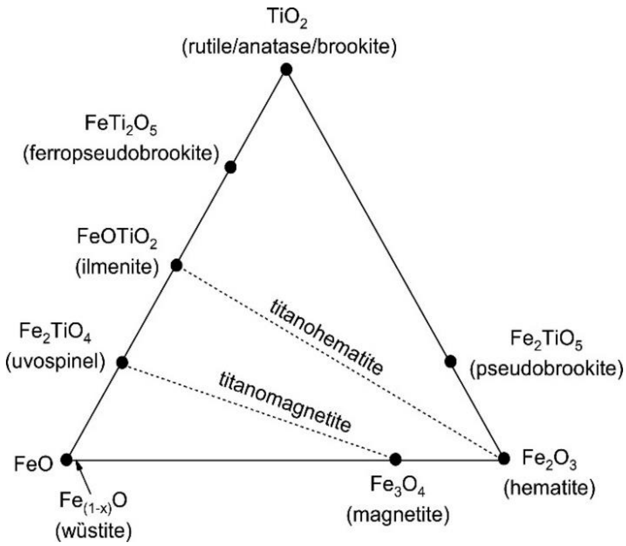

Figure 1. The approximate compositions of Ti ore minerals of commercial interest.

Figura 1. Composição aproximada dos minérios de Ti com interesse comercial.

minerals (Zhu *et al*., 2011; Nguyen and Lee, 2018; Subasinghe *et al*., 2021). The extraction of Ti derivatives was initiated in the late 19th century when ilmenite smelting was first reported in New Jersey, USA. In addition, titanium alloys were produced at the onset of the 20th century, in 1906 (Morley, 1981).

Titanium is considered an essential commodity for most modern applications, and its uses are widespread from primary to advanced applications such as paints, advanced ceramics, photovoltaic cells, gas sensors, and aircraft industries. Titanium-containing materials are thus crucial for the global economy. Therefore, this study focuses to outline the economic geology of titanium ore minerals, global distribution, applications, substitution issues, and the global production and price variations.

2. Major titanium ores and global distribution

Ilmenite (also known as ferrous titanate) is the major titanium ore, and is also the common titanium-containing heavy mineral in the global mineral trade (Subasinghe *et al*., 2021). Ilmenite crystallizes directly from melts or as oxidation-exsolution products of titanomagnetite (Dill, 2010), and it accommodates Fe_2O_3, MnO, MgO, and Al_2O_3 in its crystal structure. For this reason, ilmenite has a broad spectrum of compositions, proposed as $(Fe,Mg,Mn)_x(Fe,Al)_yTi_zO_{(x+1.5y+2z)}$ (Kucukkaragoz and Eric, 2006). Leucoxene is another major Ti ore mineral after ilmenite, and is referred to as altered ilmenite or as a mixture of pseudorutile and rutile. Leucoxene shows a broad spectrum of colours, but commonly yellow and white colours. The SiO_2 and Al_2O_3 impurity levels are comparatively high in leucoxene, but the Fe content decreases with the increment of the degree of alteration (Abdel-Karim *et al*., 2017). Rutile is the purest natural source of TiO_2. Theoretically, rutile contains 100% of TiO_2 (Dill, 2010), but it is limited to ~95% TiO_2 in nature.

The commercially interesting titanium mineral deposits have been identified in 20 countries (Fig. 2). However, China is the leading supplier of ilmenite with a share of 31% in the global market (mainly from hard-rock deposits). Australia is the second leading supplier of ilmenite with a share of 15% in the global market (mainly from unconsolidated sand deposits) (Geoscience Australia, 2013). However, Australia is the dominant supplier of rutile with a share of 52% in the global mineral market (Geoscience Australia, 2013). Apart from China and Australia, the African coastline has been an active venture for ilmenite dominant sands production since the beginning of the 19th century (Rozendaal *et al*., 2017). For example, South Africa has the potential to become an influential producer of ilmenite to the global market (Geoscience Australia, 2013; Mudd and Jowitt, 2016). However, some older titanium mineral mines in South Africa such as Cape Morgan and Umgababa ceased production since 1950s (Langton and Jackson, 1961). In addition, the African coastline is possibly the largest depository of titanium dominant heavy minerals on Earth (Rozendaal *et al*., 2017). Richards Bay of South Africa has seven heavy mineral mines with titanium-dominated ore (Rozendaal *et al*., 2017), and around 30 more mines are currently pending establishment (Tyler and Minnitt, 2004; Van Gosen *et al*., 2014; Rozendaal *et al*., 2017). The combined productions of Grande Côte in Senegal and Kwale in Kenya are some of the leading producers of global titanium feedstock (Rozendaal *et al*., 2017). Nevertheless, various common limitations such as the lack of long-term action plans, agreements such as legacy or long-term contracts, lack of investors, competitive costs for energy, competition with countries such as China, and lack of knowledge of responsible authorities have restricted most

Table 1. Chemistry and crystallography of naturally occurring titanium dominant minerals (Ren *et al*., 2000; Dill, 2010; Subasinghe and Ratnayake, 2021).

Tabela 1. Química e cristalografia de minerais naturais com titânio predominante (Ren *et al*., 2000; Dill, 2010; Subasinghe and Ratnayake, 2021).

Mineral	Chemical formula	Crystallography	TiO_2 content (%)
Rutile*	TiO_2	Tetragonal, twinned	~95%
Anatase*	TiO_2	Tetragonal, near octahedral	~95%
Brookite*	TiO_2	Orthorhombic	~95%
Ilmenite	$FeO.TiO_2$	Trigonal (Hexagonal)	40–60%
Leucoxene (commonly altered ilmenite)	$Fe_2O_3.nTiO_2$	–	>65%
Perovskite	$CaTiO_3$	Monoclinic (Pseudo cubic)	~58%
Geikielite	$MgTiO_3$	Trigonal-rhombohedral	–
Arizonite (Pseudorutile)	$Fe_2O_3.nTiO_2.nH_2O$	Trigonal-trapezohedron	–
Sphene/titanite	$CaTiSiO_5$	Monoclinic	35–40%
Titaniferous magnetite	$(Fe.Ti)_2O_3$	Isometric-hexoctahedral	–

*Polymorphic forms of titanium dioxide (anatase and brookite are low-temperature, low pressure forms) arranged in the decreasing order of abundance and these three minerals should theoretically contain 100% of TiO_2, although it is limited to ~95% in nature.

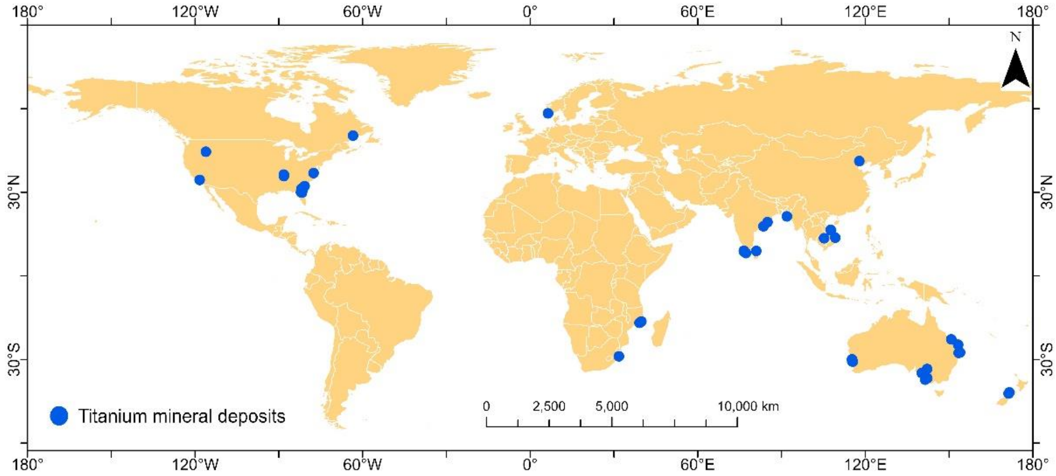

Figure 2. Global distribution of major titanium mineral deposits/producers (raw data from USGS, 2021).

Figura 2. Distribuição global dos principais depósitos/produtores minerais de titânio (dados brutos do USGS, 2021).

developing nations in Africa and elsewhere to enter the titanium mineral industries (Mudd, 2010; Subasinghe *et al*., 2021).

Tables 2 and 3 show the quantitative estimates of ilmenite and leucoxene, and rutile by different countries. In addition, tables 4 and 5 show ilmenite and rutile bearing placer deposits. Furthermore, figure 2 indicates that titanium dominant placer deposits are mainly distributed along the countries bordering the Indian Ocean, spanning from western Australia to southern Africa (Hancox and Brandt, 2000; Laxmi *et al*., 2013; Haldar, 2018; Subasinghe *et al*., 2021). Rutile was an abundant mineral in placer deposits during 1950's. Nevertheless, natural rutile has become scarcer at present because of extensive demand, exploitation, and consumption (Subasinghe *et al*., 2021). Subsequently, ilmenite and leucoxene play a major role to serve the surging demands of TiO_2 and Ti metal. A comparison of economically interested primary Ti ore deposits by country is listed in table 6, whereas table 7 represents a comparison of secondary Ti ore deposits by country.

3. Genesis of Ti mineral deposits

Titanium rich minerals are found as primary hard-rock deposits (e.g., Tellnes deposit in Norway, Damiao and Panzhihua deposits in China, and Lac Tio deposit in Canada: Tab. 6) (Dill, 2010; Perks and Mudd, 2019, 2021) and as secondary placer deposits (Tab. 7) mainly along rivers and coastlines (Amalan *et al*., 2018). Magmatic, hydrothermal, metasomatic, and metamorphic processes are important processes to develop primary deposits, whereas weathering, erosion, and transportation of sediments are important processes to develop secondary deposits (Dill, 2010; Rozendaal *et al*., 2017; Perks and Mudd, 2019).

Table 8 shows the classification of Ti ore mineral deposits. In crustal extension settings, magma differentiation, mixing, assimilation, and immiscibility dominate the genesis of primary Ti ore deposits (Charlier et al., 2006; Dill, 2010). Titanium deposits with magmatic segregation exist as major iron-titanium deposits at Lac-du-Pin-Rouge, Magpie, Canada, Sanford Lake, USA, Rødsand, Tellnes-Egersund, Norway, and Smålands-Taberg and Ulvö, Sweden (Dill, 2010; Dill et al., 2018). These deposits are mainly associated with anorthosite–gabbro–norite–monzonite (mangerite)-charnockite granite host rocks intercalated in gneisses, granulites, schists, amphibolites and quartzites (Dill *et al.*, 2018).

Fluvial, marine, and aeolian processes are crucial for the accumulation and development of secondary Ti ore deposits (Dill, 2010; Perks and Mudd, 2019). Additionally, various factors such as sea-level fluctuation, climate, tectonics, coastal geomorphology, and the composition of parental rocks are important for the formation of secondary Ti ore deposits (Rozendaal *et al*., 2017). The exploitation of unconsolidated

Table 2. Currently known global reserves of ilmenite and leucoxene (Elsner, 2010; Perks and Mudd, 2021).

Tabela 2. Reservas globais atualmente conhecidas de ilmenite e leucoxena (Elsner, 2010; Perks e Mudd, 2021).

Country	**Total resources and reserves of placer ilmenite and leucoxene (Mineral tonnage)** (million tonnes)	**Total resources and reserves of heavy minerals (Raw sands)** (million tonnes)
India	>348	>632
Australia	246	465
-West Australia	96	154
-Murray Basic	137	282
-Queensland	13	29
Mozambique	237	372
Canada	183	310–505
-Quebec	58	116
-	125	195–390
Rep. of South Africa	82	133
Kenya	61	99
Madagascar	60	60
Namibia	36	39
USA	28	58
China	22	23
Senegal	22	31
Ukraine	~14	~20
Sri Lanka	~12	~18
Malaysia	~10	~15
Vietnam	8	9
Brazil	7	10
Sierra Leone	5	~18
Kazakhstan	~3	~5
Malawi	190 [2]	>545
Total	1,400	3,000

[1] from oil sands; [2] ilmenite is not mineable due to its low TiO_2 contents, no processing industry and higher transportation costs

deposits is primarily favoured due to their size, high Ti mineral concentration, and lower mining and processing expenses. For this reason, 60% of global ilmenite and leucoxene production is derived from secondary sources, whereas the rest is derived from primary sources (USGS, 2021). In addition, total global rutile production is derived from secondary sources (Perks and Mudd, 2021).

Table 3. Currently known global reserves of rutile (modified after Elsner, 2010; Perks and Mudd, 2021).

Tabela 3. Reservas globais atualmente conhecidas de rútilo (modificadas após Elsner, 2010; Perks e Mudd, 2021).

Country	**Total reserves and resources of rutile (Mineral tonnage)** (million tonnes)	**Total reserves and resources of heavy minerals (Raw sands)** (million tonnes)
Australia	39.9	465
Western	7.4	154
Murray Basin	29	282
Eucla Basin	0.5	8
Queensland	3	29
India	>18	>632
Malawi	>13	>545
Sierra Leone	10.2	~18
Rep. of South	4.4	133
Mozambique	3.2	372
Kenya	3	99
Cameron	2.9	3
USA	2.4	58
China	0.7	23
Namibia	0.6	39
Senegal	0.6	31
Ukraine	0.5	~20
Sri Lanka	0.5	~18
Egypt	0.5	4
Kazakhstan	0.3	~5
Brazil	0.1	10
Rest	0	510
World	132	3,000

Most of the deposits with economic potential are unconsolidated placer sand deposits in coastal and shallow marine environments due to the sorting and separation of heavy minerals. Besides, the longshore currents and selective removal of lighter mineral fractions aid Ti-enriched mineral deposition (*i.e.*, black sands) near the backshore areas (Dill, 2010; Amalan *et al*., 2018). In this regard, beach/marine deposits bordering the coastline of the Indian Ocean (*i.e.*, from western Australia to southern Africa) are highly prospective for secondary Ti ore deposits (*i.e.*, ilmenite, rutile, and leucoxene). For example, the Pulmoddai deposit in Sri Lanka is the world's highest-grade ilmenite deposit, containing about 80% ilmenite (Amalan *et al*., 2018; Subasinghe *et al*., 2021).

4. Titanium ore processing into TiO_2 and Ti metal

Titanium-rich hard rocks (*i.e.*, primary deposits) are crushed, ground, and dry sieved to obtain heavy mineral sands. These powdered samples are magnetically separated into ilmenite and a by-product of titanomagnetite (Chen *et al*., 2013; Nurul, 2016; Perks and Mudd, 2019). In the secondary deposits, unconsolidated heavy mineral sands are subjected to wet sieving, gravity, magnetic and electrostatic separations to concentrate Ti ore (Nurul, 2016; Perks and Mudd, 2019).

Thereafter, pyrometallurgy, hydrometallurgy, and electrometallurgy methods are mainly used to extract/refine TiO_2 and Ti metal. Pyrometallurgy uses mechanical activation and heat treatment to convert Ti ores into synthetic rutile (Chen *et al*., 2013, Subasinghe and Ratnayake, 2021; Wijewardhana *et al*., 2021). Hydrometallurgy uses raw Ti ore, pre-treated material or synthetic rutile as feed material along with acids (e.g., H_2SO_4: sulphate route and HCl: chloride route) and/or alkaline solutions (e.g., NaOH and KOH) to extract/refine TiO_2 and Ti metal. Besides, electrometallurgy uses electrowinning and solvent extraction to extract/refine TiO_2 and Ti metal (Zhang *et al*., 2011; Nguyen and Lee, 2018). Mechanical grinding can be identified as an essential step to increase the efficiency of all the aforementioned techniques due to the increment of surface area, destruction of crystal structure, surface amorphization, and induction of chemical reactions at lower temperature and pressure (Ren *et al*., 2000; Subasinghe and Ratnayake, 2021; Wijewardhana *et al*., 2021). In contrast, high-grade feedstock such as natural rutile generates less waste compared to ilmenite and leucoxene during any of the above processing methods (Perks and Mudd, 2019). In this regard, natural/synthetic rutile is always preferred over ilmenite and leucoxene.

5. Applications of derivatives of titanium ores

Titanium minerals have several geological applications such as in provenance studies and as a pathfinding mineral for diamond exploration (Perks and Mudd, 2019; Subasinghe *et al*., 2021). Moreover, the geochemical signatures of titanium minerals are used for many geological applications. For example, TiO_2 concentration is used to examine lithological provenance (Roser and Korsch, 1999), tectonic setting (Kamikubo and Takeuchi, 2011), diagenesis (Morton and Hallsworth, 2007) and to trace weathering of source areas (Roy and Roser, 2013).

In the global context, about 95% of rutile (both natural and synthetic) is utilized to produce high-quality white TiO_2 pigments, and the rest is mainly used in the manufacture of Ti metal (Mackey, 1974; Gázquez *et al*., 2014). Titanium dioxide and Ti metal derived from titanium minerals show various properties such as high transparency to visible light and iridescence and high UV absorption. These physicochemical properties are essential for high-tech industrial applications (Haider *et al*., 2019; Subasinghe and Ratnayake, 2021), as shown in figure 3. For example, nano TiO_2 materials are used in pharmaceuticals, advanced ceramics, paints, porcelains, and rubber industries (Elsner, 2010; Zhang *et al*., 2011; Laura Wood, 2021). Consequently, the market of TiO_2 is mainly governed by the construction sector, urbanization, and technological advancements in the automotive industry. Another globally important application of TiO_2 is the ability to fabricate self-cleaning coatings for high-rise buildings (Elsner, 2010; Xu *et al*., 2013). TiO_2 can be used to produce both super-hydrophobic and super-hydrophilic surfaces (Xu *et al*., 2013). The photocatalytic activity of TiO_2 is integrated into the functioning of photovoltaic cells, gas sensors, purification filters, and electro-ceramics (Wang and Lin, 2010; Tian-Hui *et al*., 2012; Haider *et al*., 2019). In addition, the antibacterial/antimicrobial activity along with chemical inertness has made TiO_2 an indispensable material in modern food technologies (Haider *et al*., 2019). Ti metal and its alloys are used in missiles, armour plating, and naval ships due to its

Table 4. Main ilmenite bearing placer deposits in the world (modified after Elsner, 2010; Perks and Mudd, 2021).

Tabela 4. Principais depósitos placer de ilmenite no mundo (modificados após Elsner, 2010; Perks e Mudd, 2021).

Country	**Region of Deposit**	**Occurrence**	**HM-content in the sand (% by mass)**	**Proportion of ilmenite in the HM-concentrate (% by mass)**	**TiO_2-content in the ilmenite (%)**	**Percentage of leucoxene and weathered ilmenite in the HM-concentrate (% by mass)**
Australia	Western Australia	Capel	9.3	82	54.4 1)	
		Eneabba	6.2	52	59.7–69.6 1)	
		Jurien	6.3	53	54.5–63 1)	2.7
		Ludlow	0.8	77.8		7.3
		Cooljarloo	3.1	61	61 1)	3.3
	Queensland	N. Stradbroke Island	0.9	43	50.7	
	Murray Basin	Douglas	8.4	45		6
		Snapper	5.4	43		10
		Gingko	3.2	44		21.5
India	Orissa	OSCOM	20.2	66	50.8 1)	
	Tamil Nadu	Coast	7.0–39	70	54.2	
	Kerala	Chavara	9		60.6	2
Mozambique	Coast	Moma	4.3	81.6	52–60	
Sri Lanka	North-East coast	Pulmoddai	80	70–72	54.6	
Rep. of South Africa	Kwa-Zulu Natal	Hillendale	6.8	57.4	46.6 1)	0.9
		Richards Bay	13.8	~68	46–50 1)	
	Western Cape	Brand-Se-Baai	10	55	47–50 1)	
USA	Florida	Trail Ridge	3.9	36.8	64.3	14.3
	Virginia	Old Hickory	9.5	68	53.6	
Vietnam	Coast	Cat Khanh			50–51	
Australia	Western Australia	Cobum		51		11
		Dongara	10	49		2
		Jangardup South		74.9		8.4
	Murray Basin	WIM 150	4	31.6	56.1	11.6
		KWR	9.3	37		
		Culgoa		68	63	7
Gambia	Coast	Sangyang amongst others	5.2	71.3	58.2	
Kazakhstan	Northern Kazakhstan	Obukhovsky	9.4	36	55.5	8
Kenya	Coast	Kwale	3.5–6.8	68	48.9–49.3	
Madagascar	Fort Dauphin	QMM	4.5–5.5	75–80	63	
Malawi	Lake Malawi	Chipoka	33	36–79	54	
Mozambique	Coast	Congolone	3.25	77.3	53.7–57.5	
	Corndor Sands	West Block	7.5	55	1)	
Senegal	Grand Cote	total	1.8	70	54.8	
Rep. of South Africa	Kwa-Zulu Natal	Braeburn	4.7	62	1)	0.8
		Fairbreeze	5.9	58.7	1)	1.7
	Western Cape	Geel wal Karoo	42.3	21.7	50.8	1.4
Transkei	Coast	Xolobeni		54	1)	
Egypt	Eastern Rafah, Nile Delta	El Arish amongst others	4	75	34–40	
Bangladesh	Coast	Cox's Bazaar	21.9	27.6	40	2.4
Germany	Cuxhaven	Midlum	9.9	42.6	47.8	
Liberia	Coast	Total		82	on average 28	
Mozambique	Zambezi	Offshore	5	45.5	49.5	
New Zealand	South Coast	Barrytown			44–47	
Rep. of South Africa	Free State	Bothaville amongst others		59.7	55	11.4

1) processed on site; 2) estimated

Table 5. Main rutile bearing placer deposits in the world (modified after Elsner, 2010; Perks and Mudd, 2021).

Tabela 5. Principais depósitos *placer* de rútilo no mundo (modificados após Elsner, 2010; Perks e Mudd, 2021).

Country	**Area of deposit**	**Occurrence**	**HM-content in the ore sand (% by mass)**	**Percentage of rutile in the HM-concentration (% by mass)**
Australia	Western Australia	Capel	9.3	1
		Eneabba	6.2	7
		Cooljarloo	3.1	4.5
	Murray Basin	Douglas	8.4	5
		Gingko	3.2	12.1
		Snapper	5.4	15
	Queensland	N. Stradbroke Island	0.9	14
India	Orissa	OSCOM	20.2	3
	Tamil Nadu	Coast	6.0–39	5
	Kerala	Chavara	9	7
Mozambique	Coast	Moma	3.4–4.9	2.5
Sri Lanka	North-East coast	Pulmoddai	80	8
Rep. of South Africa	KwaZulu Natal	Hillendale	6.8	3.3
		Richards Bay	13.8	4
	Western Cape	Brand-Se-Baai	10	4
USA	Florida	Trail Ridge	3.9	1.7
Australia	Western Australia	Dongara	10	7
	Murray Basin	WIM 150	4	8.7
		KWR	9.3	10
		Mindarie	3.99	6.6 [1)]
Cameroon	Central	Akonolinga	0.9–1.4	0.9–1.4
Kazakhstan	Northern Kazakhstan	Obukhovsky	9.4	4
Kenya	Coast	Kwale	3.5–6.8	16
Malawi	Lake Malawi	Chipoka	33	3.2
Mozambique	Corridor Sands	West Block	7.47	0.3
Senegal	Grand Cote	total	1.8	8
Sierra Leone	Gbangbama Range	Rotifunk	1.46	40
Rep. of South Africa	KwaZulu Natal	Fairbreeze	5.9	3.3
Germany	Cuxhaven	Midlum	9.9	5.1

[1)] HM concentrate also contains additional 1.5% by mass of anatase

Table 6. Titanium ores in primary (igneous) deposits: comparison between countries.

Tabela 6. Minérios de titânio em depósitos primários (ígneos): comparação entre países.

Country	**Ilmenite (inclusive of hemoilmenite; TiO_2 Mt)**	**Titanomagnetite (TiO_2 Mt)**	**Rutile (TiO_2 Mt)**	**Total (TiO_2 Mt)**
Australia	219.5	163.9	–	383.4
Canada	326.4	109.6	–	436.0
China	819.0	~737.0	–	819.0
Finland	22.6	4.9	–	27.5
Madagascar	10.0	–	–	10.0
Norway	90.8	41.4	1.1	133.3
Poland	93.8	93.8	–	187.6
Russia	491.0	81	–	572.0
South Africa	171.9	103.1	–	275.0
Sweden	0.1	–	–	0.1
USA	25.4	–	4.0	29.4

Table 7. Titanium ores in secondary (sedimentary) deposits: comparison between countries.

Tabela 7. Minérios de titânio em depósitos secundários (sedimentares): comparação entre países.

Country	Ilmenite (inclusive of hemoilmenite; TiO_2 Mt)	Leucoxene (TiO_2 Mt)	Rutile (TiO_2 Mt)	Total (TiO_2 Mt)
Australia	182.6	37.6	48.8	269.0
India	172.6	–	–	172.6
Madagascar	41.4	2	1.0	44.4
Mozambique	132.5	–	–	132.5
New Zealand	16.8	–	–	16.8
Senegal	10.1	0.6	0.6	11.3
Sierra Leone	0.7	–	6.9	7.6
South Africa	77.4	1.2	9.1	87.7
Sri Lanka	19.4	0.1	2.2	21.7
USA	39.4	–	0.5	39.9

Table 8. Classification of Ti mineral deposits.

Tabela 8. Classificação dos depósitos minerais de Ti.

Magmatic Ti deposits	Metamorphic Ti deposits	Structure-related Ti deposits	Sedimentary Ti deposits
(i) Ti–Fe–(V) deposits related to mafic intrusions	(i) Benitoite-bearing serpentinite and glaucophane schists	(i) Sphene in Alpino-type fissure veins	(i) Ti–Nb laterites and bauxites (Ti only as by-product)
(ii) Ti-bearing metasomatized gabbros	(ii) Rutile-bearing metagabbros and eclogites		(ii) Ti alluvial-fluvial placers
(iii) Ti–Nb–Zr–REE deposits related to carbonatites and agpaites			(iii) Ti marine/aeolian placers

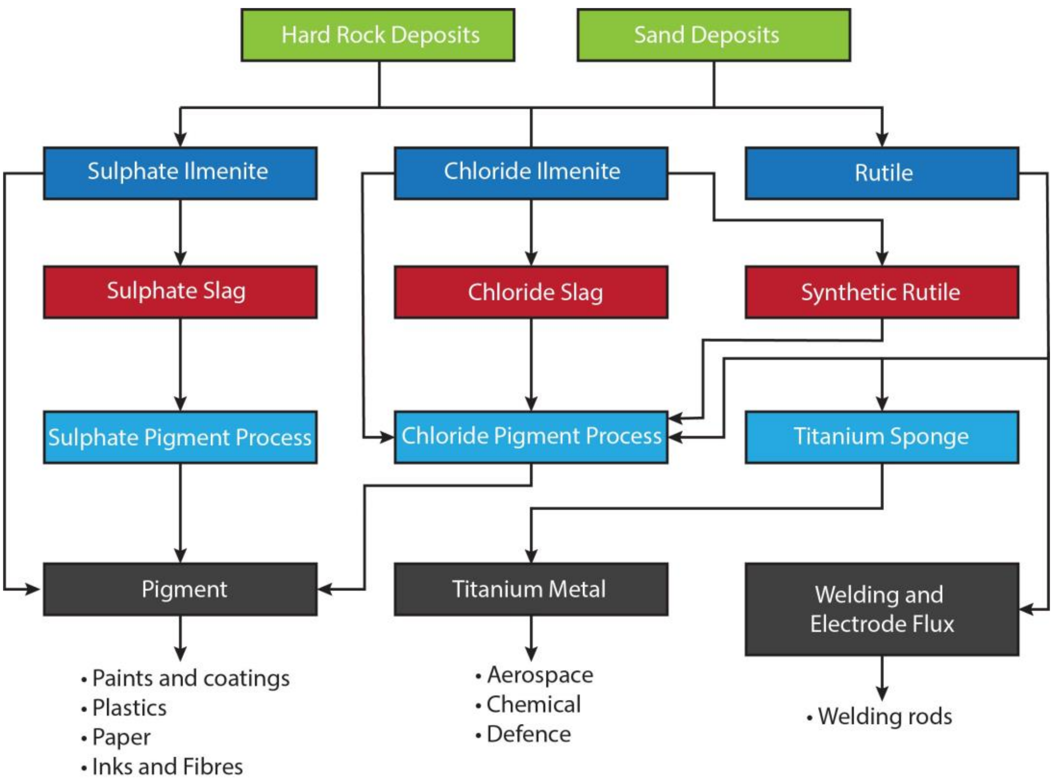

Figure 3. Structural overview of titanium minerals: applications of titanium products after separation, beneficiation, and pigment production (modified after Elsner, 2010).

Figura 3. Visão geral estrutural dos minerais de titânio: aplicações de produtos de titânio após separação, beneficiação e produção de pigmentos (modificado de Elsner, 2010).

high versatility in different environments (Gooch, 2010). Titanium metal is also used in biomedical engineering applications such as in dentistry and prostheses (Alsner, 2010; Koizumi *et al*., 2019). Titanium and its alloys contribute to about 25% of the weight of turbine engines, and titanium plays a key role in the manufacture of fasteners, landing-gear supports, springs, applications such as in dentistry and prostheses (Elsner, 2010) and a variety of other interior and exterior components in aircraft (Elsner, 2010; Laura Wood, 2021).

6. Substitution issues

Critical raw materials have unique properties making them hardly substitutable in the selected application (Girtan *et al*., 2021). In this regard, titanium dioxide is technically one of the materials difficult to substitute because of its unique chemical and physical properties such as chemical inertness, whiteness, and opaqueness, antibacterial activity, insulation, catalytic activity, photocatalytic activity, ultraviolet protection, and high melting and boiling points (Glassford and Chelikowsky, 1992; Wold, 1993; Subasinghe and Ratnayake, 2021). Titanium dioxide is potentially substitutable with lead sulphate ($PbSO_4$), zinc oxide (ZnO) and barium sulphate ($BaSO_4$). However, these substitutions are applied only in the coating and plastic industries (Haider *et al*., 2019). Therefore, the replacement of TiO_2 in other applications such as photocatalysis, antibacterial activity, and advanced ceramics are hardly possible.

Titanium dioxide and Ti metal substitutions can only be overcome by addressing the following critical issues such as (i) the substitutes must essentially be comparable with TiO_2/Ti metal, (ii) downstream industries/applications would benefit or take advantage of, (iii) the current TiO_2 market accept substitutions/new formulations, (iv) long-term abundance/availability of substitutes, (v) cost (*i.e*., affordable/cheap) of substitutes, and (vi) a continuous supply of substitutes. The industries/companies can thus answer these challenges, and would be able to introduce substitutes for TiO_2 and Ti metal.

7. Global production and price variations

7.1. Analysis

Raw data on ilmenite and rutile were obtained from the United States Geological Survey (USGS) database and mineral yearbooks over 65 years from 1950 to 2015. The two datasets were subjected to a Unit Root Test for determining stationary vs. non-stationary data using an autoregressive model. After that, non-stationary data were converted to stationary data by differencing. Seasonality was checked in these precedent data. The tentative autoregressive moving average (ARMA) values were identified, and the tentative autoregressive integrated moving average (ARIMA) models were used in the absence of seasonality. Furthermore, the tentative seasonal autoregressive integrated moving average (SARIMA) models were used in the presence of seasonal variation. The best-fitting model was identified among the tentative models using Akaike’s information criterion (AIC). These best-fitting models were tested for model adequacy using the Ljung-Box test. Consequently, the productions and prices of ilmenite and rutile were forecasted until 2025 using the generated models. In this study, the R studio software (version 1.2.5001) was used for statistical analysis and prediction.

Afterward, the compound annual growth rate (CAGR) and the mean absolute percentage error (MAPE, measure of the accuracy of prediction) were estimated for the production and price variations of each commodity. The production and price projections were categorized into three CAGR groups such as (i) CAGR $\leq$ 0: poor growth rate, (ii) 0 $<$ CAGR $<$ 5: satisfactory growth rate, and (iii) CAGR $\geq$ 5: healthy growth rate, within the confidence level of 95%. The production and price projections were also grouped into three MAPE categories such as (i) MAPE $\leq$ 10: high accuracy, (ii) 10 $<$ MAPE $<$ 20: moderate accuracy, and (iii) MAPE $\geq$ 20: poor accuracy, within the confidence level of 95%.

7.2. Interpretations

The global production (Fig. 4) and price variations (Fig. 5) suggest that the demand for most of the Ti minerals will increase along with the global population and per capita consumption during the next decade (Ali *et al*., 2017). The global annual production of ilmenite and rutile frequently underwent short-term fluctuations (Fig. 4). The calculated CAGRs for the production of ilmenite and rutile are 1.73% and 1.40%, respectively during the period of the forecast until 2025. The mean absolute percentage error (MAPE) in the production of ilmenite and rutile is 19.53% and 11.83%, respectively. It indicates moderate accuracy for predicted values. Therefore, both ilmenite and rutile will undergo satisfactory growth rates in the future. The industrial community dealing with raw materials will gain most of the benefit from these growths. According to Laura Wood (2021), the global titanium market price is expected to increase from USD 24.7 billion to USD 33.5 billion over a forecast period of 5 years from 2021 to 2026 with a CAGR of 6.3%. This market can be ascribed to derivatives of raw materials such as ilmenite and rutile. However, the Covid-19 global pandemic has decreased the demand and operations of the titanium mining and processing industries (Laura Wood, 2021).

Similarly, the global annual price variation of ilmenite and rutile underwent short-lived variations such as in 2010, mainly due to the peaking of rare earth elements (REEs) during the period of the “rare earth crisis” (Fig. 5) (Eggert *et al*., 2016). The price of rutile is expected to undergo a satisfactory CAGR of 1.40% with a moderate accuracy MAPE of 12.21% (Fig. 5). Trends of the last prices of raw data are involved in ARIMA prediction models. Therefore, the considerable price variations just before the forecast have significantly affected the projection and accuracy. Besides, the global annual production and price data of titanium minerals have an inherent uncertainty due to a lack of high-quality information on the resources and reserves estimations (Weng *et al*., 2013; Jowitt *et al*., 2018). Moreover, unclear/non-verified sources are sometimes accounted for in the production data of the two publicly sourced entities, the USGS and the British Geological Survey (BGS) (McNulty and Jowitt, 2021). Consequently, the accuracy of these interpretations is dependent on the quality of raw data.

7.3. Status of the titanium market

At present, around 25 companies predominantly are involved in the titanium industry worldwide. However, the market is highly uncertain in supply and demand. The titanium market is driven by the increase in aerospace and aircraft productions, the enormously expanding construction sector, and the development of lightweight and energy-efficient vehicles. Accordingly, various new ways of TiO_2 application have presently emerged, which would aid the titanium industry to remain on track (e.g., the incorporation of ultrafine TiO_2 particles in cosmetics and construction industries

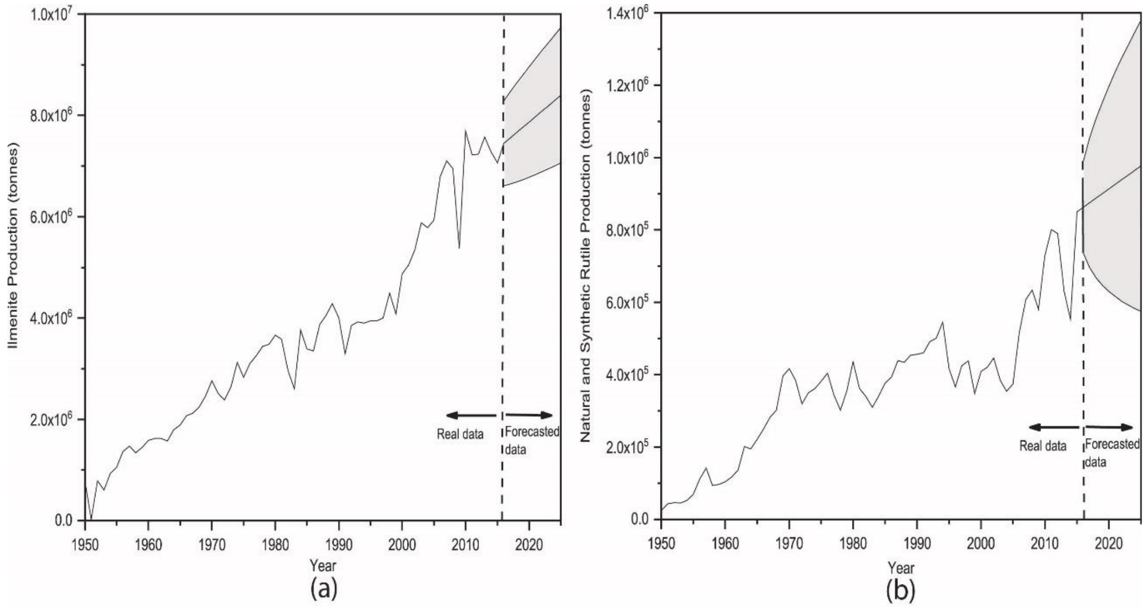

Figure 4. Global annual production of ilmenite and rutile from 1950 to 2015, and forecast of productions until 2025 (raw data from USGS, 2021). The highlighted zone indicates 95% confidence interval of the forecast.

Figura 4. Produção anual global de ilmenite e rútilo entre 1950 e 2015, e previsão de produção até 2025 (dados brutos do USGS, 2021). A zona realçada indica um intervalo de confiança de 95% da previsão.

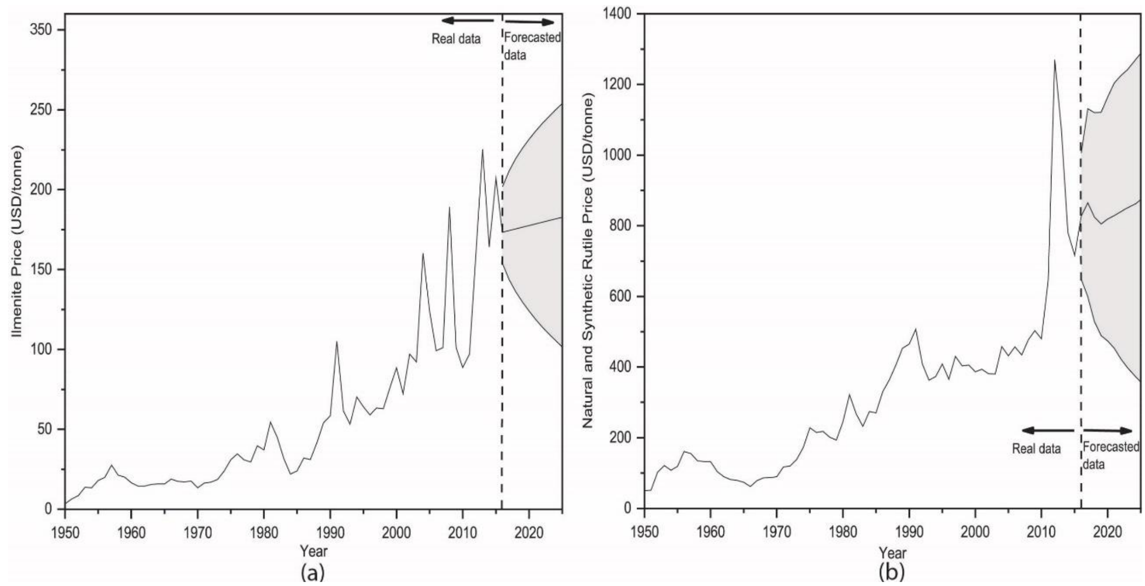

Figure 5. Unit prices of ilmenite and rutile from 1950 to 2015 and forecast of prices until 2025 (raw data from USGS, 2021). The highlighted zone indicates 95% confidence interval of the forecast.

Figura 5. Preços unitários de ilmenite e rútilo de 1950 a 2015 e previsão de preços até 2025 (dados brutos do USGS, 2021). A zona realçada indica um intervalo de confiança de 95% da previsão.

and additive manufacturing) (Laura Wood, 2021). In this case, challenges such as maintaining an uninterrupted supply chain affected by the Covid-19 global pandemic and price variation of raw minerals must be overcome to maintain a sustainable and healthy titanium industry (Laura Wood, 2021; Subasinghe *et al*., 2021).

8. Conclusions

Derivatives of titanium ores such as TiO_2 and Ti metal are almost irreplaceable materials. Therefore, Ti ore minerals such as ilmenite, leucoxene, and rutile have a solid marketplace. Rutile is preferred in the processing industry due to its high TiO_2 content. Nevertheless, low-grade feed materials such as ilmenite and leucoxene became prominent due to the geological scarcity of natural rutile. Consequently, processed materials such as synthetic rutile are used as the feedstock to extract TiO_2 and/or Ti metal. End-products (*i.e*., TiO_2 and Ti metal) are then used in a variety of primary to advanced applications such as in the military, aircraft, photovoltaic cells, pharmaceuticals, prostheses, etc. However, substitutions are extremely rare for most the applications of TiO_2. Based on the analysis carried out in this study, the production and price of rutile (*i.e*., both natural and synthetic) are expected to witness satisfactory growth. The production of ilmenite will also undergo satisfactory growth.

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References

Abdel-Karim, A. A. M., Moustafa, A. I., El-Afandy, A. H., Barakat, M. G., 2017. Mineralogy, chemical characteristics and upgrading of beach ilmenite of the top meter of black sand deposits of the Kafr Al-Sheikh Governate, Northern Egypt. *Acta Geologica Sinica*, **91**: 1326-1338. https://doi.org/10.1111/1755-6724.13364.

Ali, S. H., Giurco, D., Arndt, N., Nickless, E., Brown, G., Demetriades, A., Durrheim, R., Enriquez, M. A., Kinnaird, J., Littleboy, A., Meinert, L. D., Oberhänsli, R., Salem, J., Schodde, R., Schneider, G., Vidal, O., Yakovleva, N., 2017. Mineral supply for sustainable development requires resource governance. *Nature*, **543**: 367-372. https://doi.org/10.1038/nature21359.

Amalan, K., Ratnayake, A. S., Ratnayake, N. P., Weththasinghe, S. M., Dushyantha, N., Lakmali, N., Premasiri, R., 2018. Influence of nearshore sediment dynamics on the distribution of heavy minerals placer deposits in Sri Lanka. *Environmental Earth Sciences*, **77**: 737. https://doi.org/10.1007/s12665-018-7914-4.

Charlier, B., Duchesne, J. C., Vander, Auwera, J., 2006. Magma chamber processes in the Tellnes ilmenite deposit (Rogaland Anorthosite Province, SW Norway) and the formation of Fe–Ti ores in massif-type anorthosites. *Chemical Geology*, **234**: 264-290. https://doi.org/10.1016/j.chemgeo.2006.05.007.

Chen, G., Song, Z., Chen, J., Peng, J., Srinivasakannan, C., 2013. Evaluation of the reducing product of carbonthermal reduction of ilmenite ores. *Journal of Alloys and Compounds*, **577**: 610-614. https://doi.org/10.1016/j.jallcom.2013.06.038.

Das, G. K., Pranolo, Y., Zhu, Z., Cheng, C. Y., 2013. Leaching of ilmenite ores by acidic chloride solutions. *Hydrometallurgy*, **133**: 94-99. https://doi.org/10.1016/j.hydromet.2012.12.006.

Dill, H. G., 2010. The "chessboard" classification scheme of mineral deposits: Mineralogy and geology from aluminium to zirconium. *Earth-Science Reviews*, **100**: 1-420. https://doi.org/10.1016/j.earscirev.2009.10.011.

Dill, H. G., Goldmann, S., Cravero, F., 2018. Zr-Ti-Fe placers along the coast of NE Argentina: Provenance analysis and ore guide for the metallogenesis in the South Atlantic Ocean. *Ore Geology Reviews*, **95**: 131-160. https://doi.org/10.1016/j.oregeorev.2018.02.025.

Eggert, R., Wadia, C., Anderson, C., Bauer, D., Fields, F., Meinert, L., Taylor, P., 2016. Rare earths: market disruption, innovation, and global supply chains. *Annual Review of Environment and Resources*, **41**: 199-222. https://doi.org/10.1146/annurev-environ-110615-085700.

Elsner, H., 2010. *Heavy Minerals of Economic Importance*. Germany: Assessment Manual Bundesanstalt für Geowissenschaften und Rohstoffe (BGR), Federal Institute for Geosciences and Natural Resources, 219.

European Commission, 2022. *Internal Market, Industry, Entrepreneurship and SMEs; European Commission: Brussels, Belgium*. Available at: https://ec.europa.eu/growth/sectors/raw-materials/areas-specific-interest/critical-raw-materials_en. (Accessed on April 2022).

Gázquez, M. J., Bolívar, J. P., Garcia-Tenorio, R., Vaca, F., 2014. A review of the production cycle of titanium dioxide pigment. *Material Science and Applications*, **5**: 441-458. https://doi.org/10.4236/msa.2014.57048.

Geoscience Australia, 2013. Australia's identified mineral resources. Canberra: Geoscience Australia. Available at: http://www.australianminesatlas.gov.au/aimr/commodity/mineral_sands.html. (Accessed September 2021).

Girtan, M., Wittenberg, A., Grilli, M. L., de Oliveira, D. P., Giosuè, C., Ruello, M. L., 2021. The critical raw materials issue between scarcity, supply risk, and unique properties. *Materials*, **14**: 1826. https://doi.org/10.3390/ma14081826.

Glassford, K. M., Chelikowsky, J. R., 1992. Structural and electronic properties of titanium dioxide. *Physical Review B*, **46**: 1284. https://doi.org/10.1103/PhysRevB.46.1284.

Gooch, W. A., Ground, A. P., 2010. *The design and application of titanium alloys to US Army Platforms-2010*. International Titanium Association Titanium Conference.

Haider, A. J., Jameel, Z. N., Al-Hussaini, I. H., 2019. Review on: titanium dioxide applications. *Energy Procedia*, **157**: 17-29. https://doi.org/10.1016/j.egypro.2018.11.159.

Haldar, S. K., 2018. *Mineral Exploration: Principles and Applications*. Second ed., Elsevier, 334.

Hancox, P. J., Brandt, D., 2000. An overview of the heavy mineral potential of Liberia. *Journal of the Southern African Institute of Mining and Metallurgy*, **100**: 29-34. https://hdl.handle.net/10520/AJA0038223X_2589.

Jowitt, S. M., Mudd, G. M., Werner, T. T., Weng, Z., Barkoff, D. W., McCaffrey, D., 2018. The critical metals: an overview and opportunities and concerns for the future. *SEG Special Publication (Society of Economic Geologists)* **21**: 25-38.

Kamikubo, H., Takeuchi, M., 2011. Detrital heavy minerals from Lower Jurassic clastic rocks in the Joetsu area, central Japan: Paleo-Mesozoic tectonics in the East Asian continental margin constrained by limited chloritoid occurrences in Japan. *Island Arc*, **20**: 221-247. https://doi.org/10.1111/j.1440-1738.2011.00762.x.

Koizumi, H., Takeuchi, Y., Imai, H., Kawai, T., Yoneyama, T., 2019. Application of titanium and titanium alloys to fixed dental prostheses. *Journal of Prosthodontic Research*, **63**: 266-270. https://doi.org/10.1016/j.jpor.2019.04.011.

Kucukkaragoz, C. S., Eric, R. H., 2006. Solid state reduction of a natural ilmenite. *Minerals Engineering*, **19**: 334-337. http://doi:10.1016/j.mineng.2005.09.015.

Langton, G., Jackson, E. J., 1961. Recovery of ilmenite, rutile and zircon at Umgababa. *In*: Transactions of the 7th Commonwealth Mining and Metallurgical Congress, *SAIMM, Johannesburg*, 1072-1091.

Laura Wood, 2021. Research and market: the worldwide titanium industry is expected to reach $33.5 billion by 2026. Available at: https://www.businesswire.com/news/home/20211012006021/en. (Accessed on January 2022).

Laxmi, T., Srikant, S. S., Rao, D. S., Rao, R. B., 2013. Beneficiation studies on recovery and in-depth characterization of ilmenite from red sediments of badlands topography of Ganjam District, Odisha, India. *International Journal of Mining Science and Technology*, **23**: 725-731. https://doi.org/10.1016/j.ijmst.2013.08.017.

Mackey, T. S., 1974. Acid leaching of ilmenite into synthetic rutile. *Industrial and Engineering Chemistry Product Research and Development*, **13**: 9-18. https://doi.org/10.1021/i360049a003.

McNulty, B. A., Jowitt, S. M., 2021. Barriers to and uncertainties in understanding and quantifying global critical mineral and element supply. *Iscience*, **24**: 102809. https://doi.org/10.1016/j.isci.2021.102809.

Morley, I. W., 1981. *Black sands: a history of the mineral sand mining industry in eastern Australia*. University of Queensland Press, St. Lucia, Qld, 278. ISBN-10. 070221633X.

Morton, A. C., Hallsworth, C. R., 2007. Stability of detrital heavy minerals during burial diagenesis. *In*: Mange, M. A., Wright, D. T. (Eds.), *Heavy Minerals in Use*. Developments in Sedimentology, **58**: 215-245. https://doi.org/10.1016/S0070-4571(07)58007-6.

Mudd, G. M., 2010. The environmental sustainability of mining in Australia: key mega-trends and looming constraints. *Resources Policy*, **35**: 98-115. https://doi.org/10.1016/j.resourpol.2009.12.001.

Mudd, G. M., Jowitt, S. M., 2016. Rare earth elements from heavy mineral sands: assessing the potential of a forgotten resource. *Applied Earth Science*, **125**: 107-113. https://doi.org/10.1080/03717453.2016.1194955.

Nguyen, T. H., Lee, M. S., 2018. A review on the recovery of titanium dioxide from ilmenite ores by direct leaching technologies. *Mineral*

Processing and Extractive Metallurgy Review, **40**: 231-247. https://doi.org/10.1080/08827508.2018.1502668.

Nurul, A., 2017. *Chemical and Electrochemical Leaching Studies of Synthetic and Natural Ilmenite in Hydrochloric Acid Solution*. Perth Western Australia: Murdoch University, 344.

Perks, C., Mudd, G., 2019. Titanium, zirconium resources and production: A state of the art literature review. *Ore Geology Reviews*, **107**: 629-646. https://doi.org/10.1080/00206814.2021.1904294.

Perks, C., Mudd, G., 2021. Soft rocks, hard rocks: the world's resources and reserves of Ti and Zr and associated critical minerals. *International Geology Review*, 1-22. https://doi.org/10.1016/j.oregeorev.2019.02.025.

Ren, R., Yang, Z., Shaw, L. L., 2000. Polymorphic transformation and powder characteristics of TiO_2 during high energy milling. *Journal of Materials Science*, **35**: 6015-6026. https://doi.org/10.1023/A:1026751017284.

Roser, B. P., Korsch, R. J., 1999. Geochemical characterization, evolution and source of a Mesozoic accretionary wedge: the Torlesse terrane, New Zealand. *Geological Magazine*, **136**: 493-512. https://doi.org/10.1017/S0016756899003003.

Roy, D. K., Roser, B. P., 2013. Geochemical evolution of the Tertiary succession of the NW shelf, Bengal basin, Bangladesh: Implications for provenance, paleoweathering and Himalayan erosion. *Journal of Asian Earth Sciences*, **78**: 248-262. https://doi.org/10.1016/j.jseaes.2013.04.045.

Rozendaal, A., Philander, C., Heyn, R., 2017. The coastal heavy mineral sand deposits of Africa. *South African Journal of Geology*, **120**: 133-152. https://doi.org/10.25131/gssajg.120.1.133.

Subasinghe, H. C. S., Ratnayake, A. S., 2021. Processing of ilmenite into synthetic rutile using ball milling induced sulphurisation and carbothermic reduction. *Minerals Engineering*, **173**: 107197. https://doi.org/10.1016/j.mineng.2021.107197.

Subasinghe, H. C. S., Ratnayake, A. S., Sameera, K. A. G., 2021. State-of-the-art and perspectives in the heavy mineral industry of Sri Lanka. *Mineral Economics*, **34**: 427-439. https://doi.org/10.1007/s13563-021-00274-3.

Tian-Hui, Z., Ling-Yu, P., Su-Ling, Z., Zheng, X., Qian, W., Chao, K., 2012. Application of TiO_2 with different structures in solar cells. *Chinese Physics B*, **21**(11): 118401. DOI: 10.1088/1674-1056/21/11/118401.

Tyler, R. M., Minnitt, R. C. A., 2004. A review of the sub-Saharan heavy mineral sands deposits: implication for new projects in southern Africa. *Journal of the Southern African Institute of Mining and Metallurgy*, **104**: 89-99.

United States Geological Survey (USGS), 2021. Mineral Resources Online Spatial Data. Available at: https://mrdata.usgs.gov. (Accessed August 2021).

Van Gosen, B. S., Fey, D. L., Shah, A. K., Verplanck, P. L., Hoefen, T. M., 2014. Deposit model for heavy-mineral sands in coastal environments. Chapter L in Mineral Deposit Models for Resource Assessment, *Scientific Investigations Report 2010–5070–L*, US Geological Survey, 51. https://doi.org/10.3133/sir20105070L.

Wang, J., Lin, Z., 2010. Dye-sensitized TiO_2 nanotube solar cells with markedly enhanced performance via rational surface engineering. *Chemistry of Materials*, **22**: 579-584. https://doi.org/10.1021/cm903164k.

Weng, Z. H., Jowitt, S. M., Mudd, G. M., Haque, N., 2013. Assessing rare earth element mineral deposit types and links to environmental impacts. *Applied Earth Science*, **122**: 83-96. https://doi.org/10.1179/1743275813Y.0000000036.

Wijewardhana, T. D. U., Subasinghe, H. C. S., Ratnayake, A. S., 2021. Value addition to ilmenite using carbonized waste coconut shells: a mechanochemical approach aided with powdered seashells as a rate raiser. *Mining, Metallurgy & Exploration*, 1-15. https://doi.org/10.1007/s42461-021-00420-z.

Wold, A., 1993. Photocatalytic properties of titanium dioxide (TiO_2). *Chemistry of Materials* **5**: 280-283. https://doi.org/10.1021/cm00027a008.

Xu, Q. F., Liu, Y., Lin, F. J., Mondal, B., Lyons, A. M., 2013. Superhydrophobic TiO_2–polymer nanocomposite surface with UV-induced reversible wettability and self-cleaning properties. *ACS Applied Materials & Interfaces*, **5**: 8915-8924. https://doi.org/10.1021/am401668y.

Zhang, W., Zhu, Z., Cheng, C. Y., 2011. A literature review of titanium metallurgical processes. *Hydrometallurgy*, **108**: 177-188. https://doi.org/10.1016/j.hydromet.2011.04.005.

Zhu, Z., Zhang, W., Cheng, C. Y., 2011. A literature review of titanium solvent extraction in chloride media. *Hydrometallurgy*, **105**: 304-313. https://doi.org/10.1016/j.hydromet.2010.11.006.