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and
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Global trends in reserves, production and utilization of iron ore and its sustainability with special emphasis to India

Iron is the fourth most common element and the second most abundant metallic elementin the earth's crust. It is world's one of the most commonly used metal and primary raw material used in the steel industry. The largest concentration of iron ore is found primarily in banded sedimentary formations of Precambrian age. Iron ores of India have enormous demand in the international market due to their rich iron content. The increasing demand for iron ore worldwide in the last few years due to rapid industrialization, urbanization, and technological developments, has increased the consumption of iron ore resources exponentially. Because of limited iron ore reserve with enormous global demand, it is high time to adopt advanced techniques to extract iron from both the low- and medium-grade ores. Also, more thrust should be given on scientific exploration, exploitation, advanced mine planning, and mineral beneficiation techniques. Efforts should also be made to develop new approaches and dynamic models to address the socio-economic, environmental, geological, technological, legal, and geopolitical issues for sustainable iron ore mining. This paper discusses the geological setting, global trends in reserves, production, and utilization of iron ore resources with special reference to India for its optimum utilization and conservation for the sustainability of the future generations.

Keywords: *Iron ore; reserves; production; utilization; sustainability.*

1. Introduction

The overall development of any nation is linked with industrialization, and in turn, depends on its mineral resources. India is endowed with a diverse and abundant resource of metallic and non-metallic minerals by the mother earth, which propounded it a robust industrial base. Out of eighty-nine minerals produced in India, four are fuel, eleven are metallic, fifty-two are non-metallic, and twenty-two are minor minerals. India's abundant mineral resources include manganese, coal, bauxite, chromite, mica, iron, monazite, titanium, limestone and salt. Even today, India is one of the leading producers of iron ore and steel in the world. The other iron-rich nations around the globe are Australia, Brazil, Russia, China, and Ukraine.

The iron ore formations are generally of sedimentary origins commonly found in Precambrian marine sedimentary successions (Bekker et al., 2010; Beukesand Gutzmer, 2008; Gross, 1991, 1993, 1996; Hagemann et al., 2008; James, 1954; Klein, 2005; Thurston et al., 2008). Typically, they occur in thin-bedded or laminated chemical sediment with high iron content (Klein, 2005). Iron deposits generally occur in the form of oxides (hematite and magnetite), hydroxides (limonite and goethite), carbonate (siderite), and sulfide (pyrite). Iron is extracted from two important iron ores, hematite, and magnetite.

Based on the depositional setting, Precambrian iron formations are categorized into two types: the Algoma-type and the superior-type. The Algoma-type iron formations are inter-layered or stratigraphically linked to submarine-emplaced volcanic and hypabyssal sub-volcanic intrusive rocks in greenstone belts, and in some cases, linked to volcanogenic massive sulfide (VMS) deposits (Franklin, 1995). The Algoma-type banded iron formations (BIFs), occurring relatively in small scale, are accompanied by pyroclastic rocks in the middle-upper part of greenstone belts (Goodwin, 1962), such as BIFs in the greenstone belts of Yilgarn cratonin Australia, Abitibi in Canada and Dharwar craton in southern India. In contrast, the superior iron formations are developed in passive-margin sedimentary rock successions that generally lack direct relationships with volcanic rocks(Gross,1996).The iron ore formations constitute a major part of the chemical precipitated siliceous and carbonaceous sediments consisting of minerals formed during diagenesis and metamorphism (James, 1954; Gross, 1996; Klein, 2005; Beukesand Gutzmer, 2008; Bekker et al., 2010).

Iron ores in India are generally soft with high clay content that typically generates more fines (-10 mm size) during the ore preparation. These fines are of relatively lower grade and cannot be used directly in the blast furnace (Srivastava et al.,

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2001). The iron ores in India are typified by high iron content with a relatively higher amount of alumina as high as 7% (Sengupta and Prasad, 1990). Iron ores with alumina to silica ratio greater than one creates serious operational problems during sintering and subsequent smelting in the blast furnace.

The vast iron ore deposits of India has a total reserve of 25.24 billion tonnes. It primarily comprised hematite and magnetite. According to the UNFC system as on 1.4.2013, the hematite resources of India is 20,576 million tonnes, of which 6,607 million tonnes (32%) are reserves, and 13,969 million tonnes (68%) are remaining resources. Presently, India ranks 4th in production of iron ore after Australia, Brazil, and China. The majority of Indian iron ore deposits occur in the eastern, central, and southern parts of India in the regions of Jharkhand, Odisha, Karnataka, Chhattisgarh, and Goa (Upadhyay and Venkatesh, 2006). Madhya Pradesh, Chhattisgarh, Bihar, Jharkhand, Odisha, Goa, Karnataka, Andhra Pradesh, Maharashtra, Kerala, Tamil Nadu, and Rajasthan are the principal iron ore producing states in India.

Magnetite is another principal iron ore in oxide form. It is of magmatic origin or metamorphosed banded magnetite silica formation. According to the UNFC system as on 1.4.2013, India possesses total magnetite resources of 10,747 million tonnes, of which around 34 million tonnes are reserves, and 10,713 million tonnes are remaining resources. The major magnetite resources are located in Karnataka-7802 million tonnes (72%), Andhra Pradesh-1392 million tonnes (13%), Rajasthan-627 million tonnes (6%), Tamilnadu-507 million tonnes (5%), and Goa-226 million tonnes (2%).

This paper explores the geological setting, reserves, production, and utilization of iron ore globally with special emphasis to India. Moreover, it discusses the strategies for sustainably meeting future iron ore demands.The objective of this paper is to disseminate information regarding the global trends in reserves, production, and utilization of iron ore resources for its optimum use and conservation for the sustainability of future generations.

2. Geological setting, characteristics, and distributions of iron ore deposits

Several geological models have been developed to account the significant factors that contributed the formation and geological history of iron ore deposits (Gross, 1965, 1973; Goodwin, 1962, 1973; James and Sims, 1973; Semenenko, 1973). The models, such as deep-seated hydrothermal (Taylor et al., 2001), syngenetic and diagenetic (King, 1989), and ancient supergene (Beukes et al., 2002), postulate the origin of high-grade iron ore deposits. Extensive iron-formation took place in marine rift basins, along fault scarps, in grabens and along contemporary ocean ridges (Bischoff, 1969; Gross, 1973; Piper et al., 1975).The iron ore deposits are divided into the following groups based on the mode of occurrence and origin:

Banded iron ore formation of Precambrian age: The Banded iron formations (BIFs) form a significant part of the Precambrian greenstone belt (Melnik, 1982; Polat and Frei, 2005). The Precambrian banded iron formations belonging to marine sedimentary rocks are mainly composed of iron oxides and gangue minerals. The Fe–content of these formations generally ranges from 20 to 40% with extremely low Al_2O_3 content (James, 1954). Cross (1980) divided the Precambrian BIFs into Algoma-type and Superior-type, based on their difference in depositional environments and symbiotic rock associations.

The BIFs are considered as the sedimentary origin. Most of the BIFs were developed in the Neoarchean and Paleoproterozoic periods (3.0–1.8 Ga), whereas, the Superior-type BIFs were formed in the Paleoproterozoic period (2.5–1.8 Ga). BIFs in China were mainly formed in the Neoarchean era, and a few generated during the Paleoproterozoic, Mesoproterozoic, and Neoproterozoic era. All the BIFs in China are having different grades of metamorphism and deformation. These are low-grade banded sedimentary metamorphic iron deposits with magnetite as the significant ore mineral (Li et al., 2013). The major, trace and rare earth element geochemistry of Precambrian BIFs are utilized to decipher the contemporaneous sea water chemistry and evolution of the terrestrial atmosphere–hydrosphere–lithosphere system (Klein and Beukes, 1989; Derry and Jacobsen, 1990; Danielson et al., 1992; Rao and Naqvi, 1995; Bau and Dulski, 1996; Kato et al., 1996; Bolhar et al., 2004; Trendall and Blockley, 2004).The well-known Lake-Superior-type iron formations widely distributed in Proterozoic rocks were deposited in near-shore continental-shelf environments, whereas, the Algoma-type iron formations were found in all ages of rock (Gross, 1965).

The BIFs are very well developed in India and are similar to those of Lake Superior regions of USA, Brazil, and Venezuela. The vast iron ore deposits of eastern India form a part of the volcano-sedimentary basins containing iron and some manganese deposits belonging to the Iron Ore Group of Precambrian age (Jones, 1934). The extensive outcrops of BIFs are found in the states of Jharkhand, Odisha, Chhattisgarh, Maharashtra, Karnataka, Goa and Tamil Nadu. The most common occurrences of banded iron ore formations of India are; (a) Archaean schist belts: Jharkhand, Odisha, Karnataka, Chattisgarh, Goa (high-grade deposits), (b) Granulite terrain of South India: Tamil Nadu, Andhra Pradesh, and Kerala. Iron ores are generally found in different types: (i) Massive ore (dark brown to steel grey containing 68-70% Fe), (ii) Laminated ore (soft, friable and porous in nature containing 55-60% Fe), (iii) Shaly ore (rich in iron 60% Fe or Fe may be as low as 40% with high SiO_2 and Al_2O_3 content), and (iv) Powdery ore (soft, porous and grey-blue containing 66-69% Fe).

Sedimentary iron ore deposits of siderite and limonitic

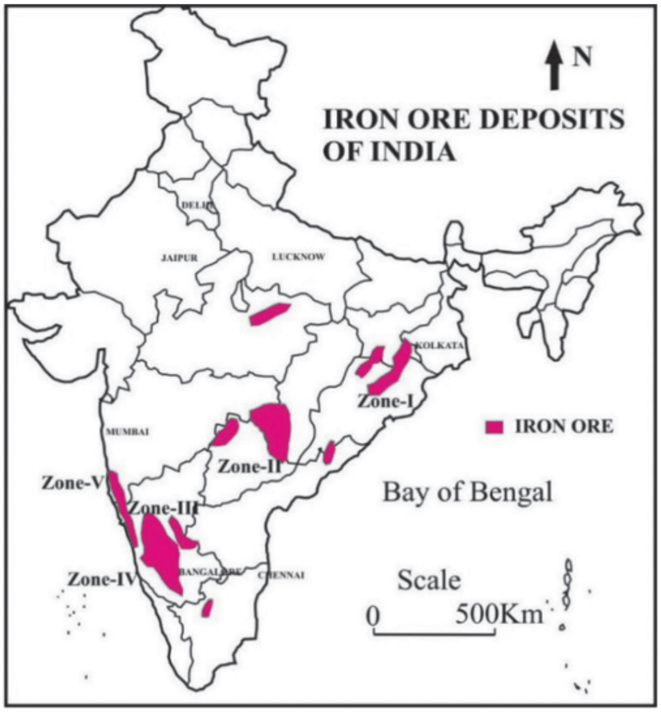

Fig.1. Distribution of iron ore deposits in India (source: Geological Survey of India)

composition: These are also known as Bog iron deposits. The ores of siderite and limonitic compositions are found in Jharkhand and West Bengal. The ferruginous beds are found in the tertiary formations of Assam and the Himalayas.

Laterite ores derived from the sub-aerial alterations: Laterite iron ores are derived from the sub-aerial alteration of rocks, such as gneisses, schists, basic lava, etc. They may consist of nodular red, yellow or brownish hematite and goethite occurring in vast stretches of deccan traps in the Chhotanagpur plateau of Jharkhand. Generally, the Goethite-lateritic ore is formed under oxidizing conditions as a weathering product of iron bearing-minerals (Klein and Hurlbut, 1985).

Ores formed by magmatic activity: A zone of apatite-magnetite rock formed by magmatic activity is closely associated with the copper belt of Singhbhum.The trace and REE patterns with strong Eu-anomalies of the iron oxide phases of banded iron-formations indicate the basinal hydrothermal ûuids as the source (Bhattacharya et al., 2007).

Titaniferous and vanadiferous magnetites: The vanadiferous-titaniferous magnetite deposits are mainly associated with ultrabasic rocks, found in eastern Singhbhum (Jharkhand), Mayurbhanj and Keonjhar (Odisha) and Hassan districts (Karnataka).

Fault and fissure filling deposits: Fault and fissure filling deposits of hematite are mainly found in the Kurnool district of Andhra Pradesh. They occur in a fault zone traversing the gneisses.

2.1 Geological distributions of iron ore deposits in India

The significant proportions of economic iron ore deposits in India are associated with the volcano-sedimentary banded iron formation (BIF) of Precambrian age. The BIF is mainly comprised Banded Hematite Quartzite (BHQ) and Banded Hematite Jasper (BHJ) (Fe ranges from 25 to 40%). In many places, the iron content of BHQ and BHJ has gone up to +55 to +65% by supergene enrichment. The magnetite deposits are generally associated with banded magnetite quartzite (BMQ). The Archean supra-crustal belts containing banded iron-formations in Jharkhand-Odisha region are commonly referred to as Iron Ore Group (Sarkar and Saha, 1962). The banded iron-formations are well-banded rocks consisting of alternating iron-rich and silica-rich layers of various thickness (Trendal, 1973).

Significant iron ore deposits distributed in several geographical locales in India are grouped under five zones on the commercial ground. They are designated as Zone-I to Zone-V (Fig.1) in different states like Jharkhand, Odisha, Chhattisgarh, Madhya Pradesh, Maharashtra, and Karnataka. In addition, the magnetite-rich banded magnetite quartzite occurs in parts of Andhra Pradesh, Rajasthan, Tamil Nadu and Kerala (source: GSI).

3. Worldwide resources and production of iron ore

According to USGS (2017), the estimated global resources of

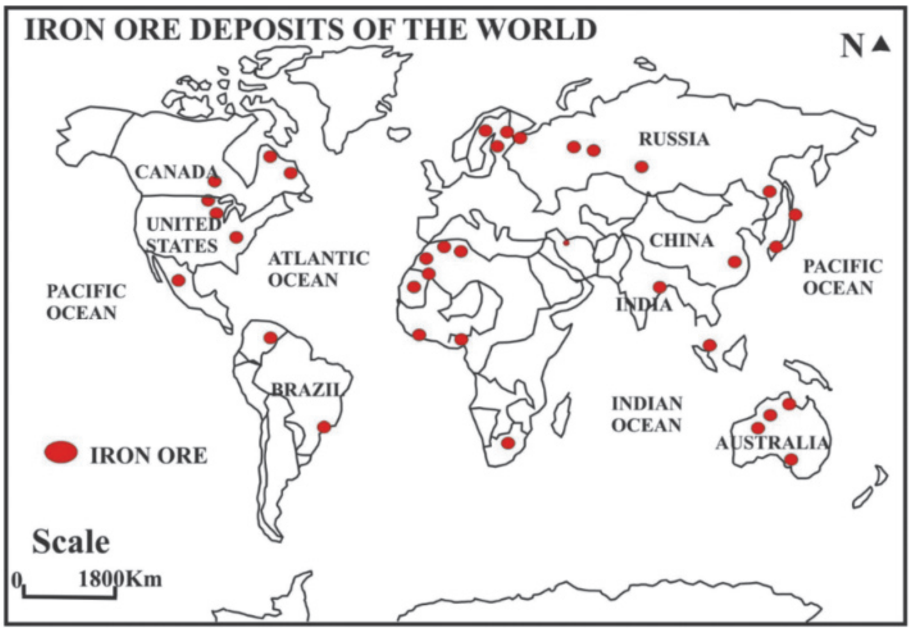

Fig.2 Worldwide distribution of iron ore deposits

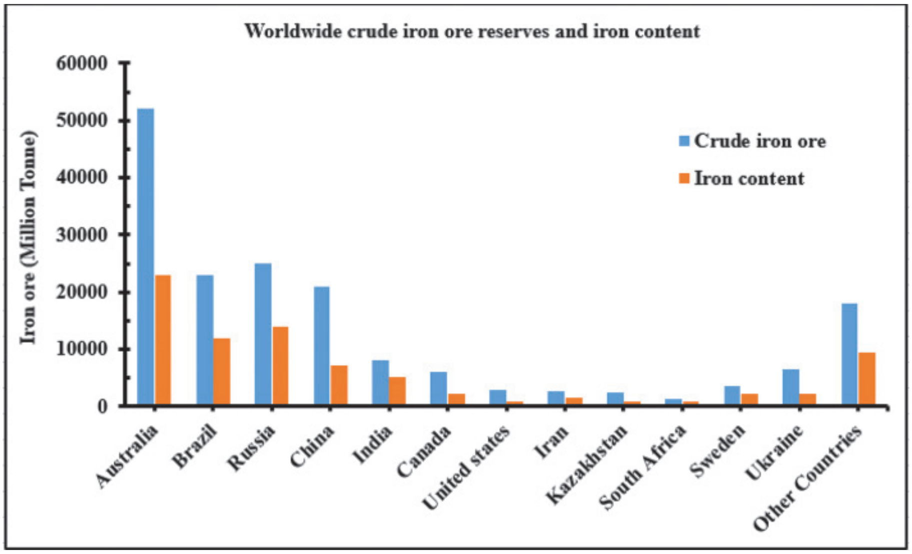

Fig.3 Distribution of crude iron ore reserves and iron content in different counties worldwide (source: USGS, 2017)

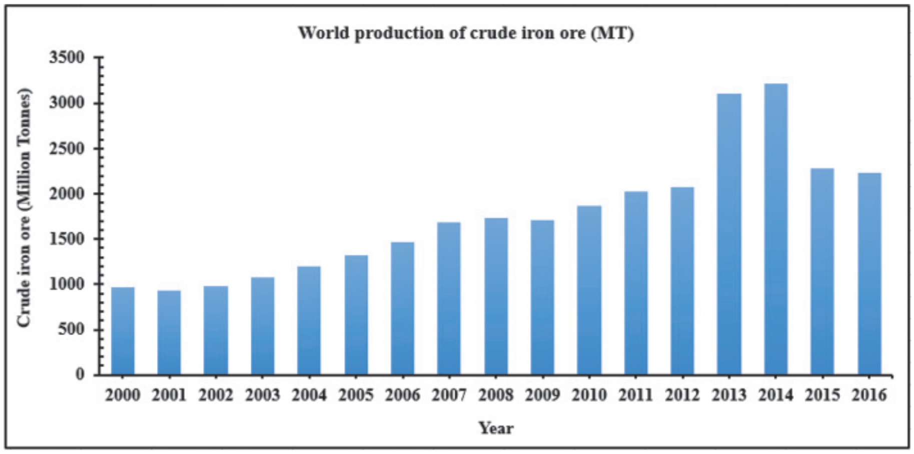

Fig.4 Worldwide production of crude iron ore from 2000 to 2016 (source: USGS2015, 2017)

crude iron ore is 170 billion tonnes, and iron ore resource is about 82 billion tonnes. The largest concentration of iron ore is mainly found in banded sedimentary formations of Precambrian age. The top ten countries in the world in terms of iron ore resources are Australia, Russia, Brazil, China, India, Canada, Ukraine, Sweden, USA, and Iran. The worldwide distribution of iron ore deposits has been shown in Fig.2. The distribution of crude iron ore reserves and iron content in different counties worldwide are presented in Fig.3.

In the last couple of years, the demand and production of iron ore have increased manifold. Fig.4 shows the consistent growth of the worldwide output of iron ore from 969 Mt in the year 2000 to 2230 Mt in the year 2016 (source: USGS, 2017). The country-wise production of crude iron ore during 2013-2016 is presented in Table 1. From the figure, a slight declining trend in iron ore production can be observed after 2014. The highest producer of crude iron ore in the world is Australia, followed by Brazil, China, and India. With a total production of about 160 Mt, India happens to be the fourth-largest producer of iron ore in the world in the year 2016 (USGS, 2017).

Table 1: Country-wise production of crude iron ore from 2013 to 2016

Country	Crude iron ore production (MT)			
	Year 2013	Year 2014	Year 2015	Year 2016
United States	53	58	46	41
Australia	609	660	817	825
Brazil	317	320	397	391
Canada	43	41	46	48
China	1,450	1,500	375	353
India	150	150	156	160
Iran	50	45	27	26
Kazakhstan	26	26	21	21
Russia	105	105	101	100
South Africa	72	78	73	60
Sweden	26	26	25	25
Ukraine	82	82	67	58
Other countries	127	131	132	120
World total	3,110	3,220	2280	2230

(Source: USGS, 2015 and 2017)

4. Resource and production of iron ore in India

4.1 Iron ore resource in India

India is one of the few countries in the world which is endowed with a vast reserve of good quality iron ore. The iron ore resource of India has increased from 5000 Mt in 1955 to 12,000 Mt in 1993 (Banerjee and Sharma, 1994). Fig.5 shows the locations of major iron ore deposits of India.

The state-wise iron ore reserves (hematite and magnetite) of India as on 01.04.2013 are presented in Table 2. From these statistics, it is evident that Odisha and Karnataka are endowed with the highest hematite and magnetite reserves, respectively. Jharkhand happens to be the second-highest hematite rich state of India. The Kiriburu iron ore deposit in West Singhbhum district of Jharkhand predominantly consists of hematite and up to 2% magnetite with varying amounts of goethite (Prasad et al., 1988). The other principal iron ore magnetite, which occurs in the form of oxide, is either of magmatic origin or

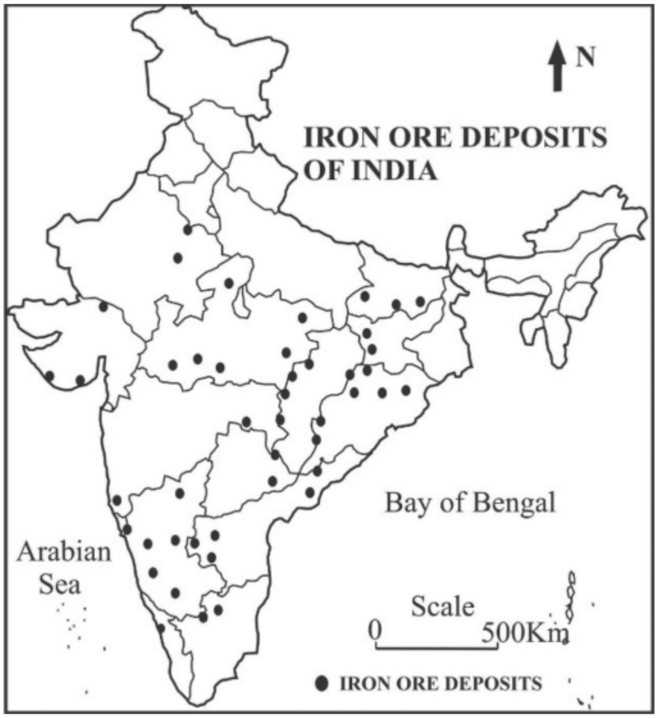

Fig.5 Major iron ore deposits of India (Source: www.geologydata.info)

Table 2: State-wise iron ore reserves (Hematite and Magnetite) of India in thousand tonnesas on 01.04.2013 (Source: IBM)

States	Reserves/Resources	States	Reserves/Resources
Hematite		Magnetite	
Andhra Pradesh	339985	Andhra Pradesh	1392027
Bihar	55	Bihar	2659
Chhattisgarh	4031303	Goa	225777
Goa	1019176	Jharkhand	10667
Jharkhand	5069082	Karnataka	7801744
Karnataka	2268819	Kerala	83435
Madhya Pradesh	253362	Maharashtra	929
Maharashtra	295636	Meghalaya	3380
Odisha	7182582	Odisha	153
Rajasthan	38941	Rajasthan	627373
Telangana	25942	Tamil Nadu	507037
Uttar Pradesh	38000	Telangana	71514

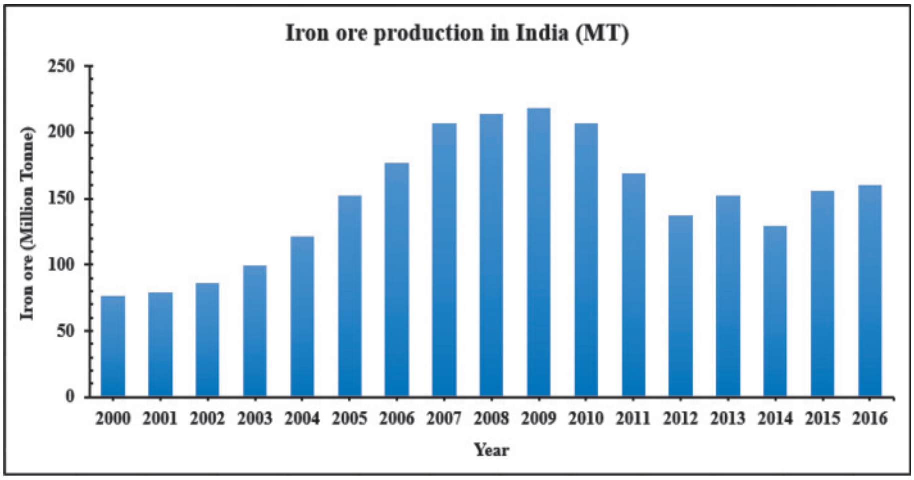

Fig.6 Iron ore production in India from 2000 to 2016 (source: USGS 2017)

metamorphosed banded magnetite silica formation. The primary magnetite resources of India are found in Karnataka, Andhra Pradesh, Rajasthan, Tamil Nadu, and Goa. The states with minor reserves of magnetite are Bihar, Jharkhand, Odisha, Meghalaya, and Maharashtra (source: IBM).

4.2. Iron ore production in India

India is a significant producer of iron ore. It contributes more than 7% of the total iron ore production of the world. The iron ore production of India from 2000 to 2016 is shown in Fig.6 (source: USGS, 2017). Odisha is the leading producer of iron ore with 52 million tonnes (40.4%) of the total production in the year 2014-15 followed by Chhattisgarh 29.4 million tonnes (22.8%), Karnataka 20.2 million tonnes (15.6%) Jharkhand 19.2 million tonnes (14.9%), and the remaining 8.1 million tonnes (6.3%) from Andhra Pradesh, Madhya Pradesh, Maharashtra and Rajasthan. The iron ore produced in India mainly consists of lumps, fines, and concentrates. The productions of iron ore from primary iron ore producing states in India during 2012-13, 2013-14, and 2014-15 have been shown in Fig.7.

5. Utilization and future prospects of iron ore resources with sustainability

The precious iron ore resource provides a strong base for the development of metallurgical industries, especially iron, steel, and alloys, of any nation. Iron ore is mainly used for making pig iron, sponge iron, and steel, together forming the largest manufactured products in the world. Hence, it is an essential commodity for modern civilization. The world population growth and iron ore production from 2000 to 2016 shown in Fig.8 indicates a consistent increasing trend (source: UN population division, 2017 and USGS, 2017). Globally, the demand for iron ore is increasing day to day, though the reserve is limited. Hence, it is necessary to use advanced techniques and give more focus on the development of new exploration methods, scientific exploitation, advanced mine planning techniques, and mineral beneficiation processes to enhance the iron recovery from the ores.

Likewise, the population growth vis-à-vis iron ore production in India during 2000 to 2016 (source: UN population division 2017 and USGS 2017) shown in Fig.9 depicts that the demand of iron ore increases with the

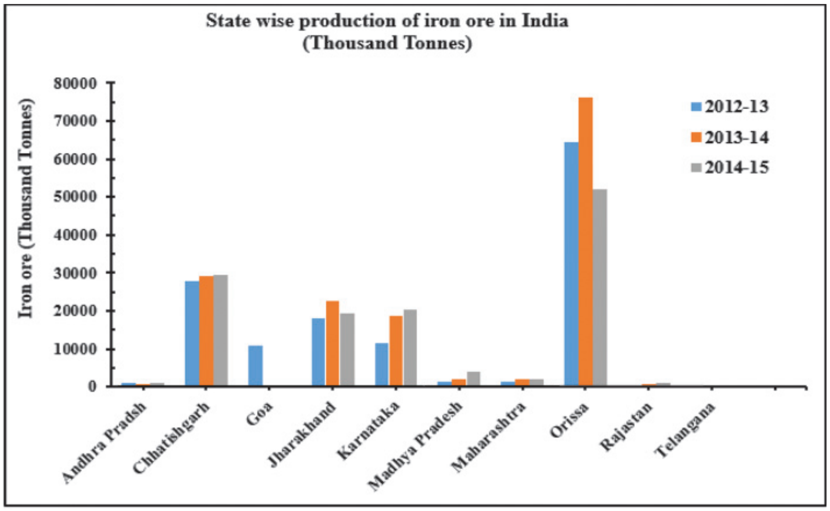

Fig.7 State-wise iron ore production in India during 2012-13, 2013-14 and 2014-15. (source: IBM)

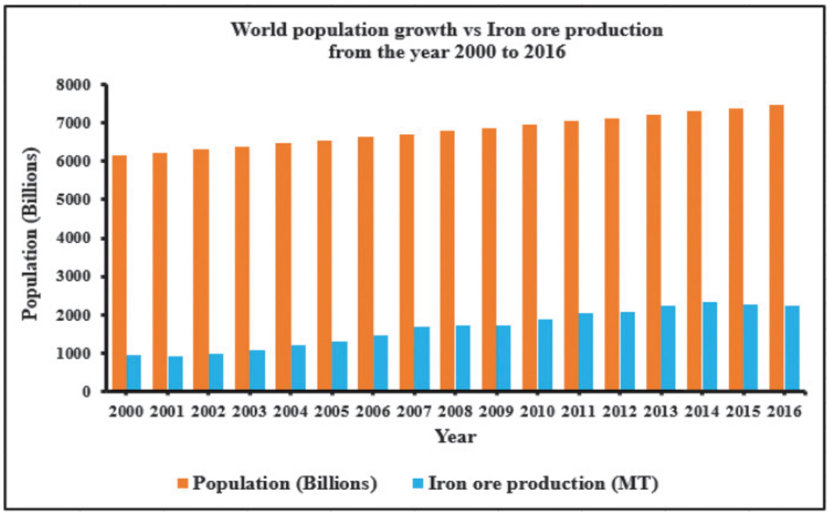

Fig.8 World population growth vis-à-vis iron ore production from 2000 to 2016 (source: UN population division 2017 and USGS 2017)

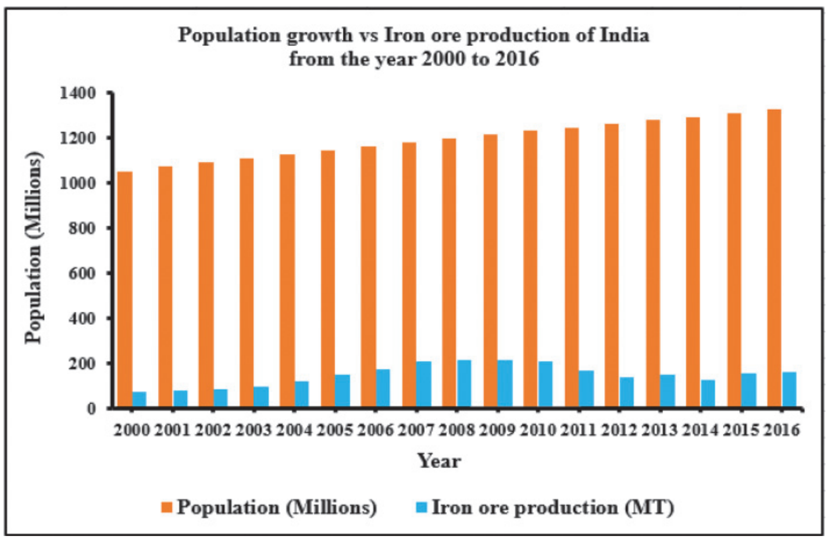

Fig.9 Population growth vis-à-vis iron ore production in India from 2000 to 2016 (source: UN population division 2017 and USGS 2017)

population growth of the country. According to IBM and USGS, total 470, 656 and 2534 million tonnes of iron ore were produced in India during 1981-1990, 1990-2000 and 2001-2016, respectively. The demand for iron ore in India is increasing day by day with the increase in industrialization. Hence, there is a need for further exploration to augment the mineral resources and bridge the gap between resources and demand. This necessitates more attention on the prospects of iron ore resource and its sustainability.

In view of the above, the following points should be taken into account for sustainable utilization and conservation of iron ore resources of the country:

(i) Discovery of new iron ore deposits through regional exploration followed by detailed exploration.

(ii) Extraction of iron ore from greater depths of the earth's crust.

(iii) Adoption of new prospects or well-designed exploration programmes and extract iron from the low-grade iron ores (<45% Fe) using developed techniques based on economic and market demand.

(iv) Adoption of advanced blast furnace-based technology in steel plants to extract iron from high-grade lumpy hematite ores.

(v) Utilization of low-grade iron ore through blending and beneficiation as adopted in other countries like Japan, Brazil, South Korea, and China.

(vi) Adoption of underground mining method for extracting iron ore in southern parts of the country like Bababudan, Kudremukh and other deposits of Western Ghats, as practiced in Kiruna, Sweden.

6. Concluding remarks

The mineral deposits and their development play a pivotal role in the economic growth of any nation. Both iron and steel are considered as the backbone of the modern economy. India has a vast resource of good quality iron ore that can meet the growing demand of domestic iron and steel industries and sustain considerable export. As the demand for iron ore is consistently increasing globally, it is necessary to adopt advanced techniques to extract iron from both the low- and medium-grade iron ores, especially from BHQ/BHJ/BMQ to meet the demand. Moreover, it is necessary to shift the trend from regional to detailed exploration and adopt advanced techniques to extract iron ore from greater depths.

Further, the advanced mine planning and mineral beneficiation processes should be adopted for utilizing the low-to medium-grade iron ores. The grade of iron can be enhanced by extracting silica and other impurities from the iron ores through the adoption of new techniques. This, in turn, will increase the iron extraction efficacy of the blast furnace. So keeping in view the scarce iron ore resources, it is high time to take necessary steps for proper exploration, exploitation, and utilization of iron ore for the sustainability of the future generations. This paper throws some light on these aspects and suggests a way forward in this endeavour.

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