JOURNAL OF GEOINTERFACE, Vol. 2, No. 2, December 2023, pp. 59–68 e-ISSN: 2583-6900

Strategic assessment of copper reserves in India: A framework for resource planning

Janmejaya Sahoo[1,2,*], Israil Khan[1,3]

[1] *Department of Applied Geology, IIT(ISM), Dhanbad-826004, India*
[2] *Geological Survey of India, Hyderabad-500068, India*
[3] *Geological Survey of India, Bhubaneswar-751012, India*

ABSTRACT
Copper mineralization in India is mainly concentrated in the Proterozoic volcano-sedimentary rocks and is predominantly located in states like Rajasthan, Madhya Pradesh, Jharkhand, Andhra Pradesh, and Odisha. Rajasthan holds India's largest share of copper reserves, followed by Jharkhand and Madhya Pradesh. India has limited known reserves of copper ore suitable for production. Hence, there is a thrust on geologists to discover new copper deposits. This review examines the major copper deposits in India, emphasizing their geological characteristics and economic implications. The major copper deposits of the country include the Khetri Copper deposit, the Neem-ka-Thana copper deposit, the Kho-Dariba copper deposit, the Mundiyawas-Khera copper deposit, the Singhbhum copper deposit, the Malanjkhand copper deposit, the Betul copper deposit, and the Ingaldhal copper deposit. Extensive research on the existing copper deposits and their classifications is highly required for the global correlation and exchange of knowledge between the countries for the management and development of existing and newly discovered copper deposits. The review also discusses the potential for increased copper consumption in various sectors and provides insights into effective economic planning and resource management to drive the country's economic growth.

ARTICLE HISTORY
Received 12 May 2023
Accepted 30 December 2023

KEYWORDS
Copper deposits
geological settings
mineralization characteristics
resource management
economic planning

1. INTRODUCTION

Copper is one of the earliest known metals with significant physical and chemical properties, has played a leading role in the development of modern society (Sahoo, 2023). It is highly valued for its excellent conductivity of heat and electricity, corrosion resistance, antimicrobial properties, and malleability. It occurs naturally in various forms and is found in sulfide, carbonate, silicate, and pure "native" copper forms. Moreover, copper is not only present in the Earth's crust but also in living organisms, where it serves crucial functions for maintaining health (The World Copper Fact Book, 2022). As a vital non-ferrous base metal, copper finds extensive applications in diverse industries such as defense, space programs, railways, power cables, telecommunications, and minting.

Copper mineralization mainly occurs in a wide variety of geologic environments among which the magmatic copper sulfide deposits, porphyry copper deposits, iron oxide copper-gold (IOCG) deposits, volcanogenic massive sulfide (VMS) or volcanic-hosted massive sulfide (VHMS) deposits and sediment-hosted copper deposits are very significant (Misra, 2000; Laznicka, 2010; Mudd et al., 2013; Sahoo et al., 2022). Different copper deposit types are characterized by their litho-association, ore mineralogy, fluid characteristics, alteration patterns, and stable isotopic signatures (Kojima et al., 2009; Dill, 2010; Sahoo et al., 2022). India, despite its growing demand

*Corresponding author. Email: jsjanmejaya@gmail.com (JS)

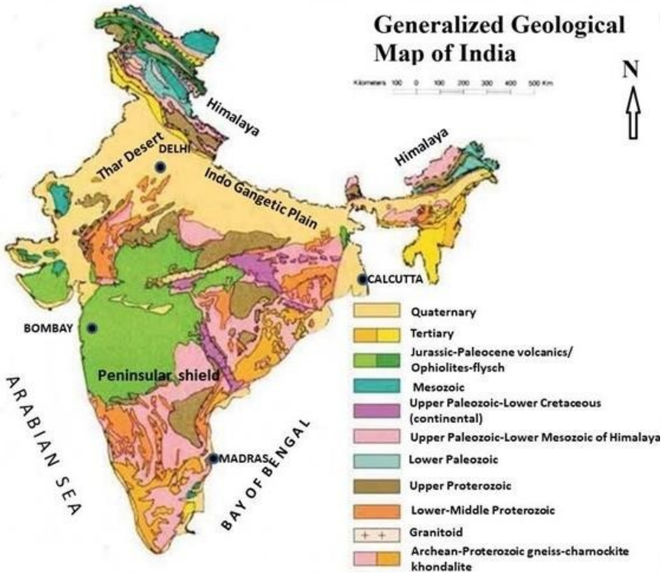

Fig. 1. Simplified geological map of India after GSI.

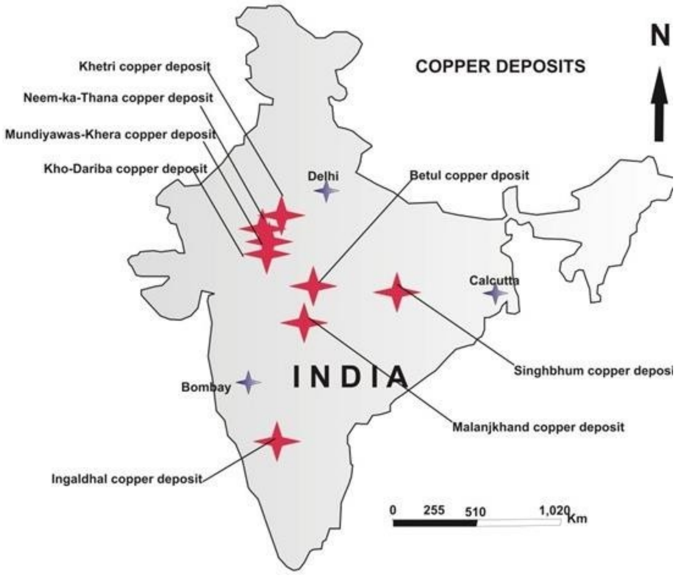

Fig. 2. India map showing locations of different copper deposits modified after Deb and Kaur (2008).

for copper, is not self-sufficient in copper ore production and the country relies on a combination of domestic production, recycling of scrap, and imports to meet its copper demands (Indian Minerals Year Book, 2021). Unfortunately, India possesses limited known reserves of exploitable copper ore, making it reliant on external sources. According to the Annual Report 2021–22 by the Ministry of Mines, India's copper reserves constitute a mere 0.31% of the world's total copper reserves. Rajasthan holds the largest share of copper reserves in India, followed by Jharkhand and Madhya Pradesh, while other states contribute to the remaining reserves (Annual Report 2021–22 by the Ministry of Mines).

This research paper provides a comprehensive overview of the major copper deposits in India, with a specific focus on their geological settings, mineralization characteristics, and associated ore bodies. By illuminating the geological aspects and economic potential of these copper deposits, this study will contribute valuable insights for policy-making, industrial practices, and academic research. This will vector to the optimal utilization of India's copper resources for the country's advancement in terms of national development, sustainable resource management, and the enhancement of socio-economic well-being.

2. GEOLOGY AND CONTROLS OF COPPER MINERALIZATION IN INDIA

Geologically, the Indian subcontinent is divided into different Cratons and fold belts (Fig. 1). Copper mineralization in India is mainly concentrated in the Archean-Proterozoic terrains (fold belts, schist belts, etc.) and associated with igneous, sedimentary and metamorphic rocks. Copper mineralizations are reported from different parts of India and are controlled by different geological factors like lithology, structure, and stratigraphy of the area. The major copper deposits are the Malanjkhand copper deposit and the Betul copper deposit in central India; the Singhbhum shear zone hosted copper deposit in eastern India; the Agnigundala copper deposit in southern India; Khetri, Mundiyawas-Khera, Kho-Dariba and Nimka Thana copper deposits in western India (Fig. 2).

3. IMPORTANT COPPER DEPOSITS IN INDIA

3.1. Khetri Copper deposit

The Khetri Copper Belt (KCB) (Fig. 3) is located in Jhunjhunun district of Rajasthan and extends about 100 km long and contains copper mineralization at Banwas, Madan Kudan, Kolihan, Chandmari, Usri, Akwali, Sathkui, Dhanaota and Charana (from north to south). The larger concentrations have been exploited by Hindustan

Copper Limited (HCL) at Madan Kudan, Kolihan, and Chandmari. At the KCB, a total resource of 83 Mt of ores with 0.88 to 1.5 % Cu was calculated (Sarkar, 2000). In Madan Kudan and Kolihan, ore bodies occur in the form of single or compound lenses hosted by garnetiferrous chlorite schist

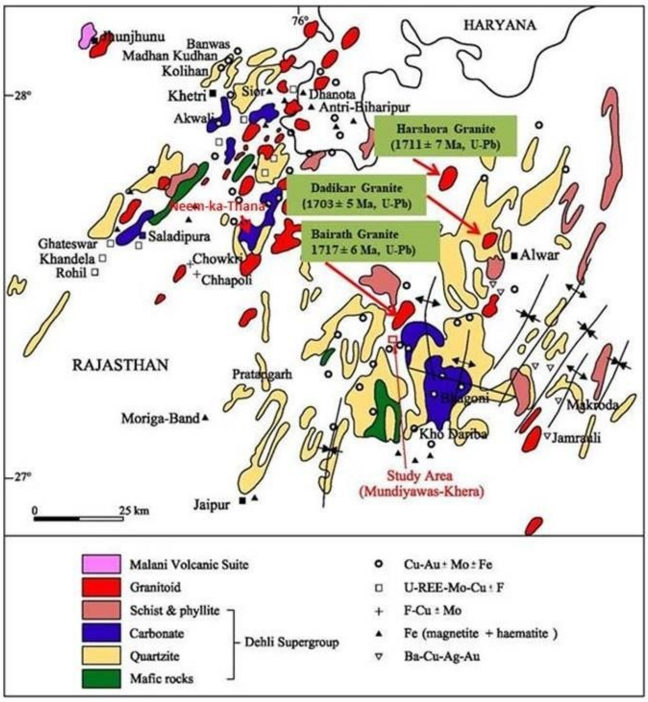

Fig. 3. Regional geological map of northern Rajasthan and Haryana showing the disposition of different copper deposits (modified after Knight, 2002). The ages of Harshora Granite, Dadikar Granite and Bairath granite are zircon U–Pb age (after Kaur et al., 2017; Sahoo et al., 2022).

and banded amphibole quartzite, while only garnetiferous chlorite schist is found in Chandmari. Carbonaceous phyllite hosts the mineralization in the south. The mineralization is concentrated at the contact of the Alwar and the Ajabgarh Group of rocks. The main sulfide phases include chalcopyrite, pyrite and pyrrhotite. Opinions about ore genesis along the KCB range from epigenetic hydrothermal to sedimentary diagenetic with later metamorphism (Deb and Kaur, 2008) to IOCG type of mineralization (Knight, 2002).

3.2. Neem-ka-Thana copper deposit

The Neem-ka-Thana copper deposit (Fig. 3) is a bornite dominated copper deposit, spread over the localities like Baleshwar, Dokan, Baniwala ki Dhani, Dariba and hosted by metapelite and dolomite (Sharma et al., 2020). The sulfide minerals that occur in the belt are mainly, bornite, chalcocite, covelite, chalcopyrite, pyrite, pyrrhotite, and minor galena and have been classified as an IOCG type of deposit. The Baleshwar copper deposit mainly consists of three parallel sub-vertical mineralized shear zones trending NE-SW. The mineralization is confined within highly-folded calc-gneisses of the Ajabgarh Group. The sulfide minerals present in the zone are chalcopyrite, pyrite, pyrrhotite, and bornite. The Cu mineralization occurs as dissemination, stringers and

lenticular patches. The reserves of the deposit are around one million tonnes of ore containing 1% Cu. Other smaller copper deposits of worth, consideration are those of the Neem-ka-Thana, Dariba, Tejawala, Ahirwala, and Chiplata areas.

3.3. Kho-Dariba copper deposit

The copper mineralization in the Kho-Dariba copper deposit (Fig. 3) is confined within phyllite and intercalated bands of arkosic quartzites of the Alwar Group of the Delhi Supergroup. The mineralization in quartzite bands and lenses is mostly of disseminated type with occasional clusters and patches of chalcopyrite. The replacement- type mineralization is confined to the southern portion of the lodes. The total strike length of the deposit is 3.3 km and consists of two main blocks viz., Dariba mine and Dariba Nala block. The Kho-Dariba deposit contains an estimated reserve of 0.56 Mt of ore at an average grade of 2.45% Cu (Dash et al., 2005).

3.4. Mundiyawas-Khera copper deposit

The Mundiyawas-Khera copper deposit (Fig. 3) is located in the Alwar basin, North Delhi Fold Belt, and nearly 5 km SSW of Thanaghazi town, Alwar district, Rajasthan. Geologically the study area is part of the Thanagazi Formation of the Ajabgarh Group in NDFB and mainly consists of volcano-sedimentary sequences (Khan et al., 2014; Sahoo et al., 2022, 2023). The litho types exposed in the study area are represented by felsic tuffs (lithic tuff, lapilli tuff, and agglometric tuff) of rhyodacite in composition interlayered with sedimentary sequences composed of quartzite, phyllite and tremolitic bearing dolomitic marble intruded by numerous quartz and carbonate veins (Khan and Sahoo, 2012; Khan, 2021; Sahoo et al., 2022, 2023). However, the dolomite and the felsic volcanic rocks are the dominant hosts for base metal mineralization. Chalcopyrite, pyrrhotite, and arsenopyrite are the dominant sulfide mineral phases observed in the area. Malachite, azurite, conichalcite, and olivenite stains are observed on quartzite, felsic volcanic rocks, and dolomite. Other sulfides are observed as veins and dissemination within host rocks. Green schist to lower amphibolite facies of metamorphism are noticed from the mineral assemblages (Mehdi et al., 2015). Structurally the area

Fig. 4. Distribution of mineral deposits along the Singhbhum shear zone (after Sarkar, 1984; Deb and Kaur, 2008).

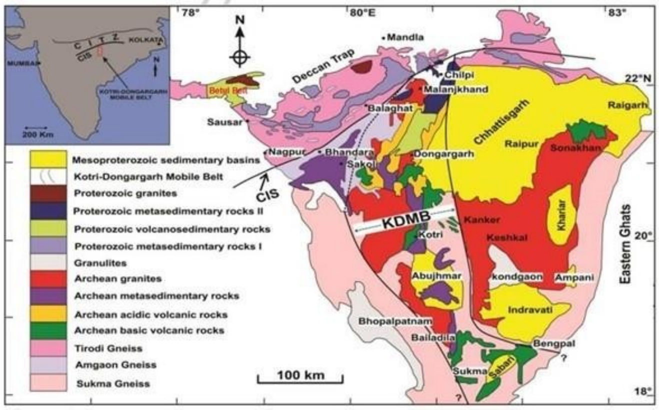

Fig. 5. Geological Map of the Bastar Craton, central India showing the Betul and Malanjkhand copper deposit (modified after Mohanty, 2012 and Asthana et al., 2016).

has undergone polyphase of deformations. Surficial expressions of mineralization are clearly visible from the freshly broken samples in the form of disseminations and veinlets of chalcopyrite and pyrrhotite in naked eye. Malachite, azurite, and goethite/hematite were mostly observed as surficial staining. The presence of ample amounts of scapolite, sericite, epidote, and carbonates on felsic volcanic rocks is presumed to be the product of intense fluid-rock interactions i.e., interactions between host rocks and the ore-bearing fluids. From the tectonic, style, geology, mineralization, and lithogeochemistry of felsic volcanic rocks of the Mundiyawas-Khera copper-gold deposits could be classified under VMS/VHMS type of deposit.

3.5. Singhbhum copper deposit

The Singhbhum thrust belt (Fig. 4), a 160 km long arcuate zone is located in the southern part of the Jharkhand state. It hosts numerous economically significant commodities like copper, uranium, and apatite-magnetite deposits. Apart from nickel, copper, and uranium ores also yield gold, molybdenum, silver, tellurium, and selenium as by-products. The copper sulfide mineralization is found all along the shear zone from Baharagora in Mayurbhanj district, Odisha in the southeast to Galudih-Duarpuram in the west of Jharkhand (Deb and Kaur, 2008). In this sector, the known deposits are located at Baharagora, Badia-Mosaboni, Dhobani-Chirudih- Samaidih, Pathargora, Surda, Kendadih-Chapri, Roam–Rakha Mines-Tamapahar, Ramchandrapahar-Byanbil- Nandup, and Turamdih-Dadkidih. The mineralization in the Singhbhum copper belt is associated with many rock types, ranging from amphibolites to chlorite schists, magnetite-chlorite-quartz schists, and albite schists. Deformation and metamorphism were applied to ore in diverse ways (Sarkar and Deb, 1974). They contain about 40 different ore minerals, both common and uncommon (Sarkar, 1984). Cu, Ni, Te, Bi, Se, Au, and Ag are the economically valuable metals recovered from them. The origin of Singhbhum's copper ores is a point of contention. Opinions vary from magmatic-hydrothermal (Dunn, 1937), albitization-related (Banerji, 1962), modified volcanogenic (Sarkar, 1984) to IOCG type of mineralization, (Knight, 2002; Pal et al., 2009).

3.6. Malanjkhand copper deposit

The Malanjkhand mine (Fig. 5) of Hindusthan Copper Limited (HCL) is India's largest open pit base metal mine. It is 90 km northeast of Balaghat in the Balaghat district of Madhya Pradesh (Deb and Kaur, 2008). Early Proterozoic calc-alkaline tonalite-granodiorite plutonic rocks include lode-type copper (-molybdenum) mineralization (Sarkar et al., 1996). The mineralized host rock has a strike length of about 2 km, a maximum thickness of 200 m., and a dip of 65 to 75 degrees along which low-grade mineralization can be traced up to a depth of 1 km. The ore deposit is estimated to be 92 million tonnes, with an average Cu grade of 1.3%. The reserves rise to 789 million tonnes at 0.83% Cu (Sikka, 1989). Sheeted quartz-sulfide veins and K-silicate alteration zones contain the majority of the mineralization. Chalcopyrite and molybdenite are the two most common primary minerals. In terms of numerous factors, and features of geology, this deposit is similar to the Precambrian (and Phanerozoic) porphyry (Sikka, 1989; Sarkar et al., 1996).

3.7. Betul copper deposit

The Betul Belt (Fig. 5) is part of the Central Indian Tectonic Zone (CITZ) (Ramakrishnan and Vaidyanadhan, 2008). The Mahakoshal Belt (2.4–1.8 Ga), which contains mafic volcanic rocks to the north, and the Sausar Belt (1.5–1.0 Ga), which contains metasedimentary rocks to the south are two major supracrustal belts within the CITZ (Roy and Prasad, 2001). The Betul Belt is surrounded by ENE-WSW trending regional shear zones and is deformed and metamorphosed to amphibolite facies. It is made up of the older Betul Gneissic Complex and a sequence of bimodal volcanics, newer metasedimentary rocks, mafic-utramafic complex and syntectonic and post-tectonic granites in a chronological order. Meta-rhyolite and meta-basalt are found in felsic-dominated bimodal volcanics in the southern and eastern parts of the Betul Belt. The eastern Betul Belt is dominated by rhyolite, with negligible basalt except for a significant band to the north. Minor bands of cherts, argillites, and exhalites are intercalated throughout the sequence. Peridotite, pyroxenite, hornblende pyroxenite, gabbro and norite are mafic-ultramafic rocks that intrude the volcanics and are thought to have formed in a continental arc environment (Roy et al., 2003, 2004). Disseminated sulfide, boxwork structure, gossanization, and secondary veins linked with significant wall rock alteration zones are all signs of mineralization on the surface. Sulfides such as chalcopyrite, pyrite, and pyrrhotite are detected in the core samples as stringers, blebs and dissemination. The concentrations of sulfides are closer to the biotitization and chloritization zones on the wall rock. Wall rock modifications seen in the Betul belt include silicification, biotitization, sericitization, carbonatization, saussuritization and epidotization (Praveen et al., 2021). Ghisi and Mouriya are placed in the western part, Banskhapa, Tarora, Bhawaratekra, Koparpani are located in the centre segment, and Biskhan, Bhuyari, Jangaldehri are located in the eastern segment of the Betul belt (Raut and Mahakud, 2004; Golani et al., 2006; Praveen and Ghosh, 2007, 2021). There are physical differences in the host rocks, alteration assemblages, and metal content among the deposits. However, depending on a specific field and typical geochemical properties, all deposits are classified and categorized as part of the VMS deposits (Lydon, 1984; Lentz, 1998; Galley et al., 2007).

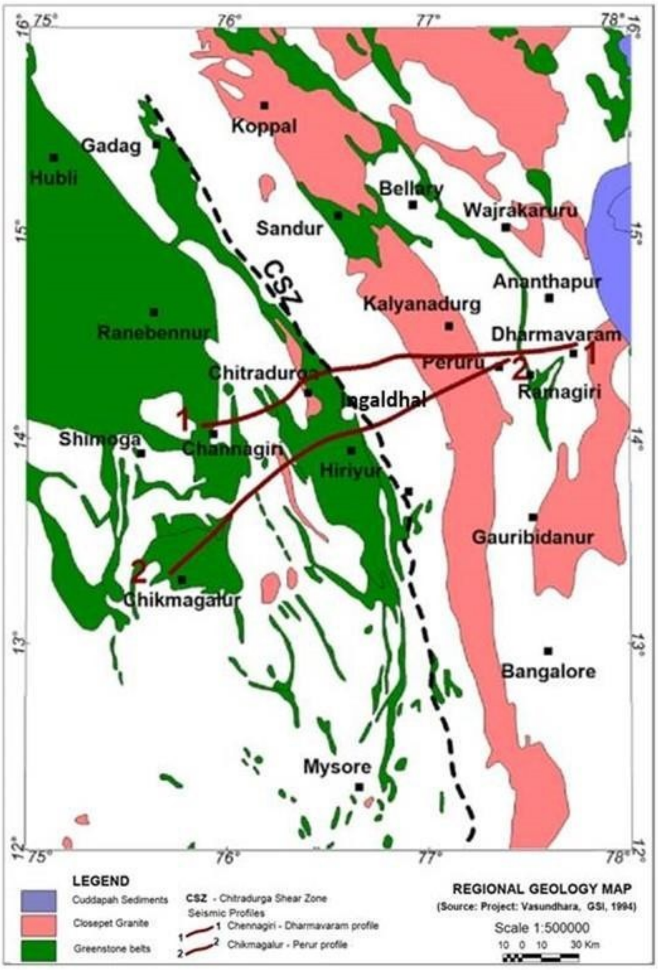

Fig. 6. Regional geological map of the central part of Dharwar Craton showing the major geological domains and the major tectonic division and Ingaldhal copper deposit (after Jayananda et al., 2013a; Rao et al., 2021).

3.8. Ingaldhal copper deposit

The Ingaldhal copper deposit (Fig. 6) is located within the Chitradurga Group of volcanic rocks at Ingaldhal, a few km away from the town of Chitradurga. This is an important copper deposit in the Chitradurga Group of the Dharwar Supergroup in southern India. This small deposit has a resource of 1 Mt @ 1.4% Cu in stratiform and vein-type mineralization. The stratiform ores are found as a 7 km long banded sulfide-chert mass. Pyrite, pyrrhotite, and magnetite are the most common minerals in the ores, with chalcopyrite and sphalerite as minor phases supported by pyritiferous carbonaceous phyllite. Within altered basaltic rocks, the vein ores are lensoid enti-

Table 1. State-wise copper reserves of India (Indian Minerals Year Book, 2021).

State	Reserves share in (%)
Rajasthan	53.81
Jharkhand	19.54
Madhya Pradesh	18.75
Other States	7.9

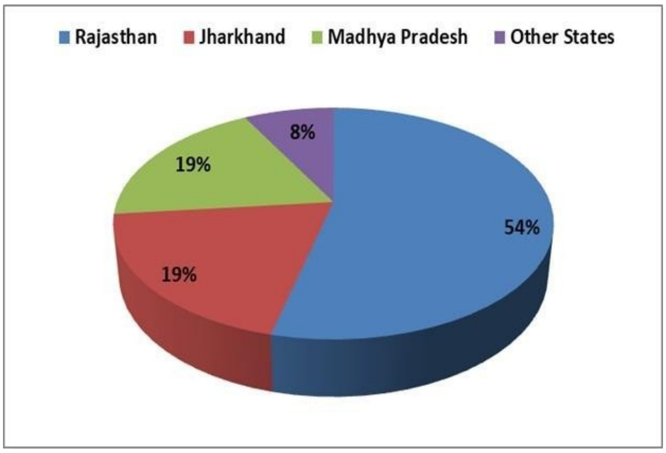

Fig. 7. Pie chart showing state-wise copper reserves of India (Indian Minerals Year Book, 2021).

ties that extend a few hundred metres along strike. The primary component of the ore is chalcopyrite, which is followed by pyrite and pyrrhotite. Upper greenschist facies of metamorphism has been noticed in this area. Most workers agree that these ores belong to the "volcanogenic type" (AnanthaIyer and Vasudev, 1985; Sarkar, 1988).

4. DISCUSSION

India has very limited known reserves of copper ore exploitable for copper production. As of April 1, 2015, the country's total copper ore resources were estimated to be 1511.50 million tonnes, containing approximately 12.16 million tonnes of copper metal. Among these resources, 207.77 million tonnes (13.74%) fall under the Reserve category, with 2.73 million tonnes of copper metal, while the remaining 1303.73 million tonnes (86.25%) are classified as 'Remaining Resources', containing 9.42 million tonnes of copper metal. Rajasthan holds the largest share of copper ore reserves in India, accounting for 813.33 million tonnes (53.81%), followed by Jharkhand with 295.39 million tonnes (19.54%) and Madhya Pradesh with 283.43 million tonnes (18.75%) and the remaining 7% of reserves are distributed among other states, including Andhra Pradesh, Gujarat, Haryana, Karnataka, Maharashtra, Meghalaya, Nagaland, Odisha, Sikkim, Tamil Nadu, Telangana, Uttarakhand, and

Table 2. Country wise copper reserves of the world (Indian Minerals Year Book, 2021).

State	Reserves share in (%)
Chile	23
Peru	9
Australia	11
Russia	7
Mexico & USA	6
Poland	4
China	3
Congo	2
Kazakhstan	2
Zambia	2
Other Countries	31

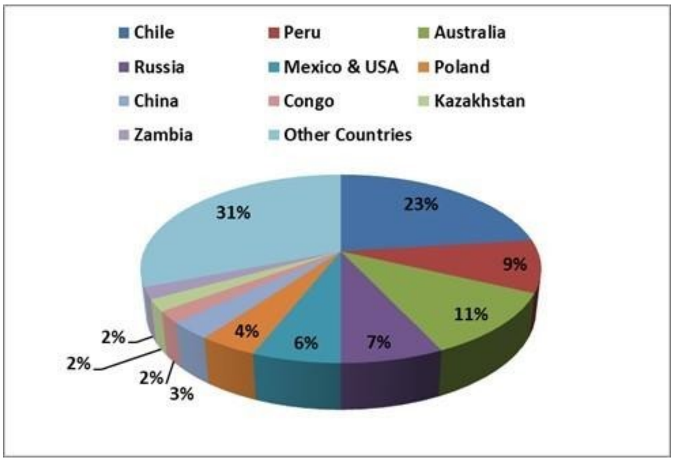

Fig. 8. Pie chart showing country-wise copper reserves of the world (Indian Minerals Year Book, 2021).

West Bengal (Table 1 and Fig. 7) (Annual report 2022–23, Ministry of Mines). India's share of the world reserve is around 0.31% only. According to the United States Geological Survey (USGS), total global copper reserves amount to 880 million tonnes (Mt) of copper (The World Copper Fact Book, 2020, Indian Minerals Year Book, 2021). Globally, Chile has the largest reserves of copper followed by Australia, Peru, Russia, Mexico, USA, Indonesia, and China are the other countries (Table 2 and Fig. 8).

The copper production trend exhibits significant fluctuations rather than a consistent pattern, varying annually over the past seven years. Analysis of copper production data from 2015 to 2021, as reported in the Indian Mineral Yearbook, indicates a notable peak during the 2014–2015 period and a subsequent decline, reaching its lowest point in 2020–2021 (Table 3 and Fig. 9).

4.1. Implications for Economic Planning

In India, the per capita consumption of copper was remarkably low at 0.5 kg in the year 2019–20, especially when compared to other countries such as

Table 3. Copper production in India from the years 2014–15 to 2020–2021 (Indian Minerals Year Book, 2015, 2016, 2017, 2018, 2019, 2020, 2021).

Year	Copper ore production (in million tonnes)
2014–15	3.59
2015–16	3.91
2016–17	3.85
2017–18	3.68
2018–19	4.13
2019–20	3.95
2020–21	3.38

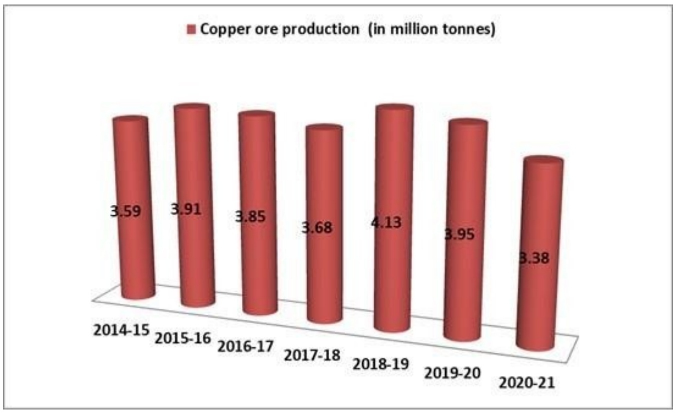

Fig. 9. Bar diagram showing copper production of India from the year 2014–15 to 2020–2021 (Indian Minerals Year Book, 2015, 2016, 2017, 2018, 2019, 2020, 2021).

Table 4. Country-wise per capita consumption of copper (Indian Minerals Year Book, 2021).

Country	Per capita consumption (kg)
Germany	13.6
Italy	8.9
USA	5.5
China	5.4
Russia	3.3
India	0.5

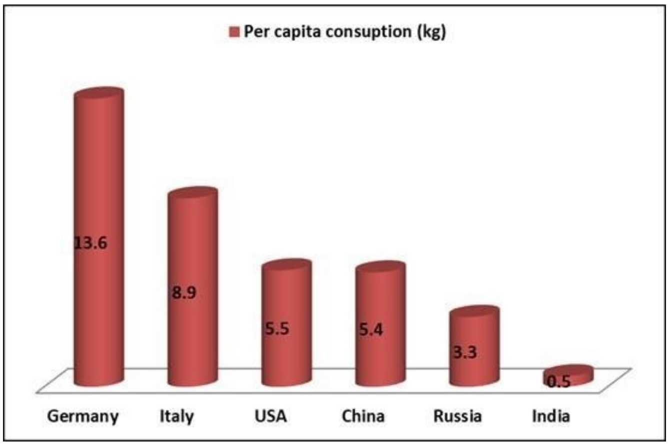

Fig. 10. Bar diagram showing country-wise per capita consumption of copper (Indian Minerals Year Book, 2021).

Russia (3.3 kg), China (5.4 kg), USA (5.5 kg), Italy (8.9 kg), and Germany (13.6 kg) (Table 4 and Fig. 10) (Indian Minerals Year Book, 2021). Copper is primarily consumed by the electrical/electronic industry due to its outstanding conductivity, as well as by the semiconductor industry for the production of copper chips. It is also extensively used in the construction industry, automobile industry, industrial machinery, and consumer products like coinage, utensils, and copper-based alloys such as brass and bronze (Table 5 and Fig. 11). Copper plays a vital role in the economies of both developed and developing countries. The mining, processing, recycling, and manufacturing of copper into various products not only creates employment opportunities but also generates wealth. These activities contribute to the development and maintenance of a country's infrastructure, while also fostering trade and investment prospects. Copper is expected to continue playing a significant role in economic planning for the advancement of society in the future.

4.2. Resource Management

The demand for copper will continue to be met through various means, including the discovery of new deposits, technological advancements, efficient design, and the recycling and reuse of copper. Copper is one of the most recycled metals, and the ability to recycle it repeatedly makes it a sustainable material of choice. Recycling copper not only extends the efficiency of its use and saves energy but also contributes to ensuring a sustainable source of metal for future generations (The World Copper Fact Book, 2020; Indian Minerals Year Book, 2021). Geoscientists, policymakers, industry stakeholders, and resource managers play a crucial role in the efficient utilization and management of copper deposits in India. To achieve this, they can propose strategies that promote sustainable mining practices, encourage investments in copper exploration and production, optimize the utilization of copper resources for economic development, and conduct comprehensive geological research on existing copper deposits. Establishing global connections would facilitate the exchange of knowledge and technology for the discovery of new copper deposits. Additionally, conducting studies on beneficiation can help identify appropriate uses for by-products, while implementing effective strategies for overburden management and mining planning is essential. By adopting these measures, India can effectively harness its copper resources for long-term economic growth and development.

Table 5. Consumption of copper in various industries (Indian Minerals Year Book, 2021).

Copper consumption	Share (in percentage)
Electrical and Telecommunication Industry in total consumption	56%
Transport	8%
Consumer Durables	7%
Building & Construction	7%
General Engineering goods	6%
Other industries including Process Industries	16%

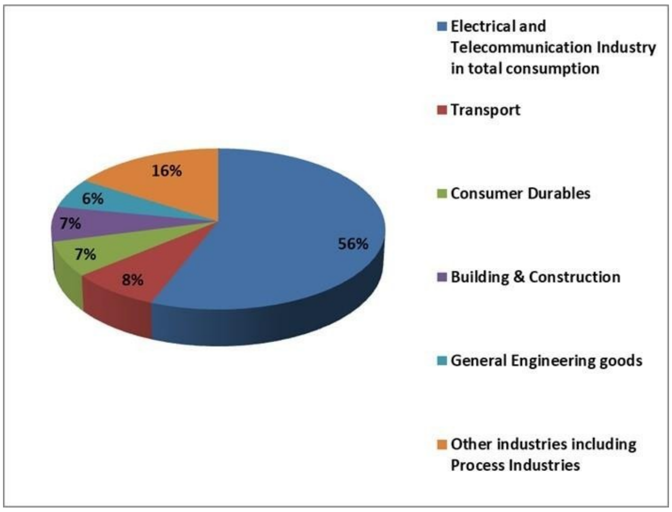

Fig. 11. Pie chart showing consumption of copper in various industries (Indian Minerals Year Book, 2021).

5. CONCLUSIONS

The geologic environments of copper mineralization in India encompass various deposit types, each with unique characteristics. Understanding the litho-association, ore mineralogy, fluid characteristics, alteration patterns, and stable isotopic signatures of these deposits are essential for effective resource management. Efficient resource management, technological advancements, and recycling practices play a vital role in meeting the demand for copper and ensuring its sustainable use. Recycling copper extends the efficiency of its use, saves energy, and contributes to a sustainable source of metal for future generations. The versatility and wide range of applications of copper in industries such as electrical/electronics, construction, transportation, and consumer products make it an indispensable metal. However, India's per capita consumption of copper is relatively low compared to other countries, indicating the potential for increased consumption and the need for further development in various sectors like electrical/electronic industry, construction, transportation, and industrial machinery industries. India's limited reserves of copper ore necessitate careful management and utilization of available resources. The country's demand for copper is growing, and it is crucial to effectively utilize India's copper resources for national development and sustainable resource management. By harnessing India's copper resources and promoting efficient utilization, reducing dependence on imports, and enhancing self-sufficiency, the country can drive economic growth, create employment opportunities, and contribute to a sustainable future. The review of copper deposits in India has provided valuable insights into the geological aspects, economic potential, job creation, infrastructure development, environmental management, scientific research, and national security. It provides valuable insights that guide policy decisions, promote sustainable development, and contribute to the overall socio-economic well-being of the nation. With the growing demand for copper in the country, it is crucial to effectively harness India's copper resources with the discovery of concealed mineral deposits through mineral system approach for national development and sustainable resource management. By leveraging these resources, reducing dependence on imports, and enhancing self-sufficiency, India can drive economic growth, generate employment opportunities, and contribute to a sustainable future.

ACKNOWLEDGMENTS

The authors are thankful to the Director, Indian Institute of Technology (Indian School of Mines), Dhanbad for supporting research work and to the Geological Survey of India (GSI) for extending necessary support during field studies. This work is part of the author's Ph.D. thesis, and they would like to thank IIT(ISM) Dhanbad, for providing laboratory facilities during the research work. The authors are thankful to their supervisor and co-supervisor for their efficient guidance and support. The authors acknowledge the Director General, Geological Survey of India (GSI) for permitting them to continue the Doctoral degree.

CONFLICT OF INTEREST

The authors have no conflict of interest regarding this work.

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