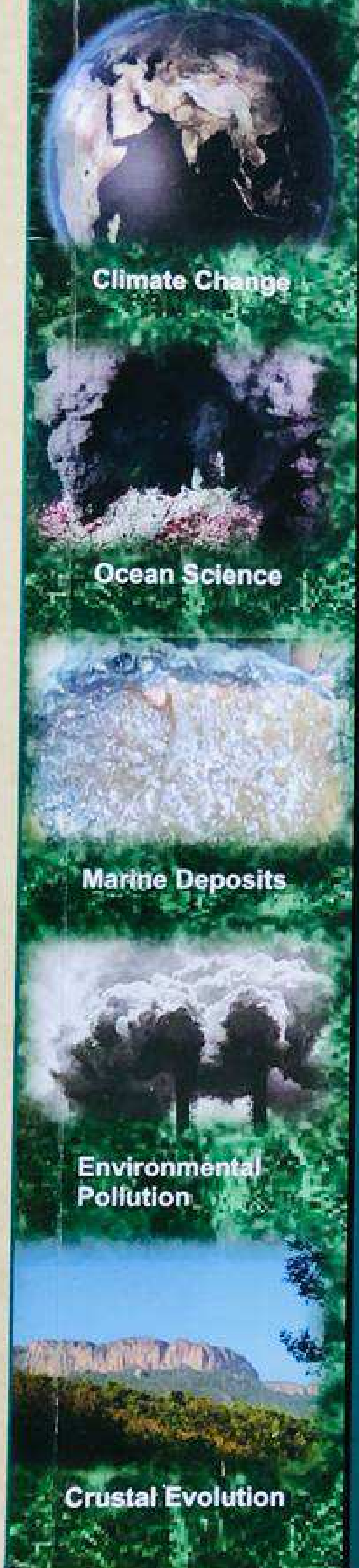
ISSN 0972-1967

Vol.23 July & October, 2021 No. 3 & 4

JOURNAL OF APPLIED GEOCHEMISTRY



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JOURNAL OF APPLIED GEOCHEMISTRY
Vol. 23, No. 4 (2021)

JOURNAL OF APPLIED GEOCHEMISTRY

Vol. 23 **October 2021** **No. 4**

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Journal of Applied Geochemistry
Vol. 23, No. 4 (2021). pp. 261-275

21ST CENTURY PROSPECTS OF GOLD BIOMINING IN INDIA -A REVIEW

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Abstract

Biomining is a natural, eco-friendly technique which is employed on commercial scale for the extraction of metals. Biomining is a process of conversion of an insoluble metal such as metal sulfides into a soluble form using microbes. Biomining has been applied to extract metals such as copper, cobalt, and gold from sulphide and/or iron containing ores typically using prokaryotes or fungi which is commercially applied using engineered dumps, heaps and stirred tanks. The geology of the mineralized areas in India, rich in chalcopyrite/pyrite, allows a number of microorganisms to be used for the extraction of metals by bio-oxidation. India is endowed with rich deposits of zinc, iron ore, manganese ore, gold, bauxite, silver, lead, tin, copper and chromite. This paper reviews the current status of biomining operations around the world, identifies factors that are important while applying biomining technology, describes the problems and prospects of biomining of auriferous deposits of India.

Keywords: Gold; Biomining; Auriferous deposits; non-ferrous; India; Bio-oxidation; Iron and sulpher oxidizing bacteria.

1. Introduction

Biomining is a natural, ecofriendly process of conversion of an insoluble metal such as metal sulfides into a soluble form using microbes which is employed on a commercial scale for the extraction of metals.Traditional methods of biomining uses extreme heat and hazardous chemicals and non-environment friendly techniques whereas bioleaching employes microorganisms to facilitate the extraction of metals from sulphide or iron-containing ores or concentrates (Rawlings 2002). Biomining has huge advantages over traditional methods (Fig. 1) and this mechanism is gaining importance and is being applied in the recovery of Gold (Brombacher et al. 1997; Chingwaru et al. 2017), Manganese (Acharya et al. 2003; Das et al. 2011), Uranium (Siddiqui et al. 2009) and Copper (Schnell 1997).

During the global financial crisis in 2008, price of gold increased by 6% where as the price value of important minerals such as nickel, zinc and copper fell by 40% (Shafiee and Topal 2010). Each year, global gold mining adds approximately 2,500-3,000 tonnes to the overall above-ground stock of gold. While gold production has shown an upward trend in recent years (2016-2017), this is likely to level off in the coming years (World Gold Council). Gold demand may rise because of reasons which includes the rising demand for gold jewellery, increasing demand for electrical products such as like mobile phones and computers which contain gold as a base component. Gold demand may also rise due to emergence of gold as a secure investment, replacing more volatile assests such as stocks, currencies and real estate (Shafiee and Topal 2010). The demand for gold has raised the price to USD$1721 per ounce (1st March 2012). Table-1 gives the details about the rise in gold prices from (2012 -2017) due to increased demand.

India has rich deposits of minerals including zinc, iron ore, manganese ore, gold, bauxite, silver, lead, tin, copper and chromite. In india, gold is presently produced from three mines viz. Hutti , Uti, Hirabuddni in Karnataka and as a by-product from base-metal sulphide deposits of Khetri (Rajasthan), Mosabani, Singhbhum (Jharkhand), in public sector and Kudrekocha in private sector (Chandra et al. 2014) but still India is the world's biggest gold importer (Fig. 2) after China and spends more than $30 billion a year buying gold from abroad, making the metal its second-biggest import item after crude oil (Federal Mines Ministry of India).

2. Indian Gold market

India's gold market is driven primarily by the consumption and fabrication of gold and both these factors have a significant impact in terms of economic value addition, contribution to foreign exchange earnings, employment, and trade balance. Gold has made a direct contribution of more than $30 billion to the Indian economy in 2012 as per the recent report (2013) commissioned by

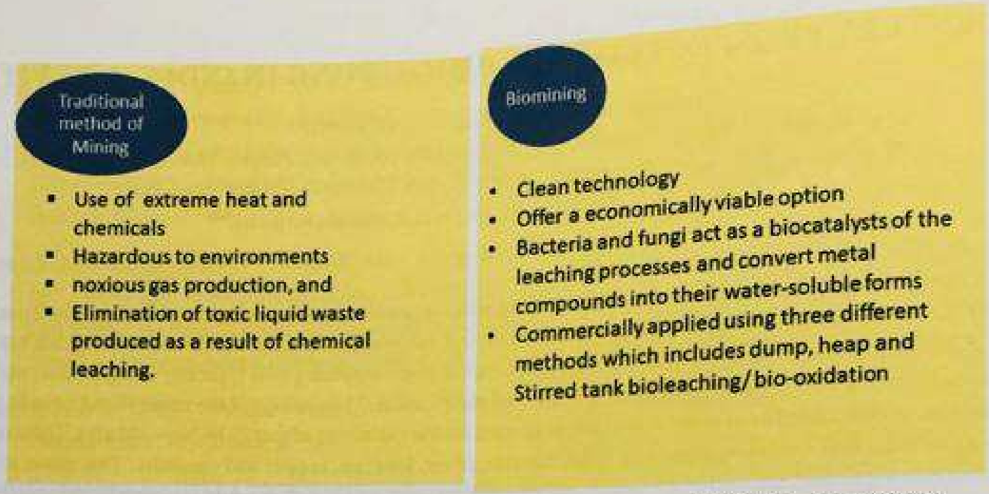

Fig. 1. Advantage of Biomining (Compiled from Brombacher et al.1997; Rawlings 2002).

Table 1. Gold prices from (2012 - 2017) due to increased demand

Year	Prices of gold in USD$
2012	1721
2013	1579
2014	1298
2015	1169
2016	1243
2017	1204

Source: LBMA, Datastream, BullionDesk/FastMarkets, World Gold Council (2015)

the World Gold Council from Price Water House Coopers. India is one of the largest gold jewellery exporters in the world. Indian gold jewellery shipments came to US$8.6bn during the financial year 2015–2016, with around half delivered to UAE, India's largest jewellery export destination. India's gold stocks are around 23,000- 24,000 MT. In India, highest market share for gold demand of 40% is in Southern India, western India at 25% and northern and eastern India have 20% and 15% of the market share respectively (World Gold Council). Indian gold refining capacity jumped in recent years from a mere three or four refineries in 2013 to 30 in 2015, taking the total capacity above 1,450MT. Gold market has also made a sizeable contribution to employment. According to a report by the consultants, AT Kearney, commissioned by the Federation of Indian Chambers of Commerce and Industry (2013), the gems and jewellery industry employs over 2.5 million people having the potential of adding a further 0.7–1.5 million by 2020.

3. Occurrence of gold

Gold is a precious metal that is valued for its beauty as well as being conductive and malleable. These properties make gold valuable both in industry and in economy. Gold occurs in free elemental form as well as nuggets or grains in rocks, veins and in alluvial deposits. Gold is a noble metal with the average concentration in the Earth's crustal rocks and soils to be 5ng g-1 (Goldschmidt, 1954). Gold occurs in solid solution series with silver and is naturally alloyed with copper and palladium. Gold occurs naturally in the universe and is thought to be produced in supernova nucleosynthesis and is present in the dust from which it is formed. On Earth, gold occurs in two forms primary and secondary. Primary form of gold occurs widely in the biosphere and in various rocks such as in case of igneous rocks (<50 mg.103Kg-1), sedimentary rocks (< 200 mg.103Kg-1), metamorphic rocks (Korubushkina et al. 1983). Under Earth's surface conditions, primary gold is progressively transformed by mechanical and (bio)geochemical processes, ultimately resulting in secondary grains and nuggets, which commonly occur in eluvial and alluvial deposits, so called placers (Southam et al. 2009; Reith et al. 2013). Secondary Au is highly pure (>99 wt. % Au), finely crystalline (0.01–5 ìm), and occurs as nano-

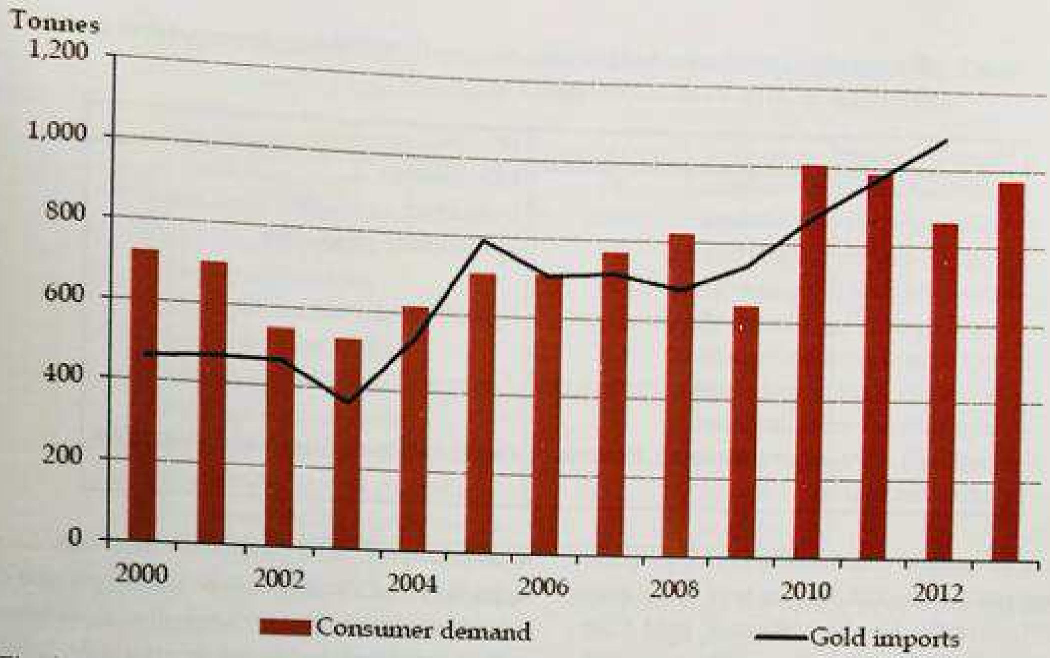

Fig. 2. Dependance of India on gold imports (Source GFMS-Thomson Reuters(2015), World Gold Council, 2015).

particulates, bacteriomorphic, sheet-like and wire Au, as well as euhedral, hexagonal, octahedral and pseudo-trigonal micro-crystals, which can aggregate to form mm-sized grains (Reith, McPhail and Christy, 2005; Falconer and Craw 2009; Southam et al. 2009).

4. Geomicrobiology and biogeochemistry of gold

Bacteria, archaea, fungi and algae play critical roles in driving the carbon-, nitrogen, sulfur-and phosphorus cycles as well as many metal cycles (Ehrlich 1996). A variety of mineral oxidizing bacteria (iron oxidizing such as Acidithiobacillus ferrooxidans, Leptospirillum ferrooxidans and Leptospirillum ferriphilum, the sulfur-oxidizing Acidithiobacillus thiooxidans and Acidithiobacillus caldus) are known to break down gold-hosting sulfide minerals in zones of primary mineralization and release the associated gold (Table-2). These microbes form biofilms on metal sulphides such as gold bearing pyrites, arsenopyrites and obtain metabolic energy through metabolic pathways such as Sulphur oxidase pathways (Sox) and reverse Dsr pathways (Friedrich et al. 2005). Morphological and media studies of Mogo mine soils has indicated the presence of microorganisms which may be actively mediating a gold cycle and bacteria and fungi were found to be capable of precipitating gold colloidal sollutions (Reith, 2006).

Ralstonia eutropha also known as Cupriavidus metallidurans, Wautersia, and Alcaligens eutrophus (Vandamme and Coenye 2004) is a facultative chemolithoautotrophic b-proteobacterium having a high tolerance to heavy metals (Janssen et al. 2010). This unique property of bacteria makes it the organism of priority for biomineralization of heavy metals from their respective toxic forms from the environment. In moderate and wet tropical climatic zones of Australia, C. metallidurans was detected in biofilm formed on the surface of gold grains which indicated that bioaccumulation may lead to gold biomineralization by forming secondary "bacteriomorphic" gold and increasing the duration of viable C. metallidurans cell exposure to Au(I)-complexes that results in an increased amount of gold uptake(Reith and McPhail 2006).

Chromobacterium violaceum is a Gram-negative non-pathogenic bacterium (facultative anaerobe) found in tropical and subtropical areas of several continents (Duran et al. 2010; Liu et al. 2016). C. violaceum produces

Table 2. Microorganisms involved in Au biomining (Source: Compiled from Brombacher et al. 1997; Rea et al. 2016; Reith and McPhail, 2007).

Micro-organisms	Microbial processes
Acidothiobacillus ferroxidans	Fe oxidation
Acidothiobacillus thiooxidans	S-oxidation
Fe- and S-oxidizer (A.ferroxidans), Actinomycetess (Streptomycetes fradiae)	Thiosulphate production
Cyanide producing bacteria (Pseudomonas spp, Chromobacterium violaceum)	Cyanide production
Bacteria such as Corynebacterium glutamicum, Fungi such as Penicillium spp	Amino acid production
Fungi such as Fusarium oxisporum, Bacteria such as Bacillus sp	Bio-reduction of Au-passive absorption

cyanide as a secondary metabolite and this property serves to degrade cyanide and thus has been found to be the most effective for bio-dissolution of gold from different materials because of its cyanide-associated metabolic activities.Previous studies have shown that C. violaceum and Bacillus megaterium are known to synthesize the enzyme b-cyanoalanine synthase which converts cyanide into b-cyanoalanine during the late stationary and death phase. Therefore, this strain can potentially be used in ecological Au recovery methods (Duran et al. 2010), (Table-3).

5. Gold biomining -present status

Biohydrometallurgy is an interdisciplinary field consisting areas of research such as geomicrobiology, microbial ecology, hydrometallurgy and microbial biogeochemistry (Rossi, 2001) which includes solubilization of metal compounds from ores. Leaching technology is divided into three main types and can be carried out at three different levels-first at the laboratory scale, the pilot scale and the commercial scale. Laboratory scale leaching can be obtained by various means such as by stationary or shake flask (Kang 1994) or air lift percolators (Chavarie et al. 1993). Whereas in the case of pilot scale the procedure is carried out on columns or in agitated tanks or reactors. At commercial scale, the procedure is carried out on industrial scales such as at mining industry or mining sites (Table-4). The microbial mineral processing and microbial hydrometallurgy of metal sulphides is currently a well established technology (Gahan et al. 2012). Over the past years, there has been a huge amount of development with regards to understanding of both its engineering perspective as well

Table 3. Microorganisms potentially useful in Au Biomining.

Microorganisms	Role in biosphere
Arthrobacter spp., Corynebacteriumsp., Deinococcus sp., Kocuriasp., Microbacteriumsp., Micrococcus spp., Propionibacteriumspp.	1. Mediate initial colonization on the grains 2. Produce EPS 3. Conditions the grain surfaces
Pseudomonasspp., Burkholderiaspp., Methylobacterium sp. Acinetobacter sp. Pseudomonasspp.	Production of EPS to further stabilize the biofilm
S-oxidizing or cyanide producing bacteria, e.g. Diaphorobacter sp., Sphingomonasspp. and Methylobacteriumsp., Sphingomonasspp.	Au solubilization
C.metallidurans, D.acidovorans, Stenotrophomonassp., . Achromobacterspp., Halomonas sp. and Herbaspirillumsp	metal-resistant bacteriawith the ability to detoxify Au-complexes.

Table 4. Commercial Gold bioleaching/ Biooxidation plants (Source: Compiled from Brombacher et al. 1997)

Plant and location	Size MT/day	Technology
Suzdal, Kazakhstan,Asia	196	BIOX®
Kokpatas, Uzbekistan,Asia	1,069	BIOX®
Laizhou, China,Asia	100	BACOX
Jinfeng, China,Asia	790	BIOX®
Sansu, Ghana, Africa	960	BIOX
Fairview, South Africa	40	BIOX
Wiluna, Australia	158	BIOX
Beaconsfield, Australia	70	BacTech
Harbour Lights, Western Australia	40	BIOX®
Fosterville, Victoria, Australia	211	BIOX®
Sao Bento, Brazil, South America	150	BIOX

as the fundamental approach with reference tomicroorganisms. The present research work and patents available on biomining techniques of gold are listed in Tables 5 and 6.

6. Gold deposits in India

The total reserves of gold ore in India are shown in the (Table-7). Initial estimates by the Mineral Exploration Corporation Limited have shown reserves worth $1.17 billion in the mines and around $880.28 million in gold-bearing deposits is estimated to be left over in residual dumps from earlier mining operations and these mines have a huge potential.

Geochronological data of gold metallogeny has revealed major periods of enrichment during the Archaean and Proterozoic periods. Gold occurs in multiple geological environment and settings such as in greenstone belts, mantle derived intrusions, diaperic juvenile plutons and granulites. As per the Geological Survey of India, prominent granite-greenstone belts of Peninsular Shield are located in Dharwar, Bastar,

Table 5. Biomining of gold-Present status

Project	References
Microbial oxidation of gold ores and gold bioleaching	Olson 2003
Biogenic production of cynide and its application in gold recovery	Campbell et al. 2001
Biorecovery of gold	Eisler 2003
Potential for the Utilisation of Micro-Organisms in Gold Processing	Reith and McPhail 2007
Studies on how biomining can serve as a useful approach toward metal extraction, microorganisms useful in biomining, and mining mechanisms	Siddiqui et al. 2009
Use of biotechnology in gold exploration and processing	Zammit et al. 2012
The potential use microorganisms in the biooxidation of gold ore from a mine in Bulawayo	Matsvayi 2016
Improving gold recovery from refractory gold ores through biooxidation using iron-sulfur-oxidizing/sulfur-oxidizing mixotrophic bacteria	Mubarok et al. 2017
Studies on potential for biotechnology for extraction of metals in Zimbabwe	Chingwaru et al. 2017

Table 6. Patents on biohydrometallurgical ore processing (1989-2018)

Inventor/Publication date assignee	Patents	Treated material	Microorganisms	References
Louisiana State University, Baton Rouge,USA	US 5.021.088	Carbon Containing Au ore	Heterotrophic fungal and bacterial strains-Thiobacilli	Portier 1991
Geobiotics Inc., San Francisco, USA	EP 0.432.935	Au ore	Chromobacterium violaceum, Chlorella vulgaris	Kleid et al. 1991
Bac Tech (Australia) Pty. Ltd., Nedlands, Australia	WO 92/16667	Sulfidic material	Autotrophic, acidophilic, Thermotolerant bacteria	Spencer et al. 1992
Newmont Mining Corp., Denver, USA	EP 0.522.978	Sulfidic ore	Thiobacilli, Leptospirillum ferrooxidans	Hill and Brierley 1993
Geobiotics Inc., Hayward (Calif.), USA	WO 95/15403	Sulfidic ore	Thiobacillus ferrooxidans	Kohr 1995
Yellowstone Environ. Sci. Inc., Bozeman, USA	WO 96/00308	Sulfidic ore	Sulfate- and hydrogen-reducing bacteria	Hunter et al. 1996
Geobiotics Inc., Hayward (Calif.), USA	WO 96/12826	Sulfidic ore	Thiobacillus, Sulfolobus and Sulfobacillus strains	Kohr et al. 1996

Table 7. Gold reserves in India

Mineral	Reserves (MT)	Remaining resources (MT)	Total resources (MT)
Ore (Primary)	24,124,537	469,570,375	493,694,912
Metal (Primary)	110.54	549.30	659.84
Ore (Placer)	-	26,121,000	26,121,000
Metal (Placer)	-	5.86	5.86

Source: Indian Bureau of Mines (2018)(http://www.ibm.nic.in)

Singhbhum and Rajasthan cratons. The Dharwar craton, which is divided into eastern and western blocks (Rogers, 1986) hosts the maximum number of gold occurrences. Primary gold is progressively transformed by mechanical and (bio)geochemical processes, ultimately resulting in secondary grains and nuggets, which commonly occur in eluvial and alluvial deposits, so called placers and also in laterite, soil and regolith. GSI has done a lot of work on gold occurrence in a variety of geological settings in India which is shown in Table-8. GSI has reported the presence of gold in Soil (0.035-4.25 ppm); termite mounds (0.025 to 0.07ppm), pegmatites (0.035 to 0.25ppm) and metabasalt (0.045 ppm) in Gadwal Schist Belt in Andra Pradesh (Ananda Murthy S, Bhattacharjee 1997). In the state of Assam and Bihar, gold associated with placer deposits has been reported in rivers such as Subarnarekha and Subansiri rivers (Radhakrishna and Curtis 1991; Radhakrishna 2002). There are reports on the occurrence of Au in the interstitial spaces of sand grains as rounded, flattened and dendritic grains, ranging in size from 20 to 200 microns in Archaean crystallines granites, gneisses, patches of greenstones and basic dykes, conglomerate, in Bhima Basin, in the state of Karnataka (George 1995). Association of gold with lateritic forms of rocks has been reported in Nilambur Valley of Kerala and values from 0.06 to 0.16 ppm in 1aterite and powdery ore of Keri and Kalne, Sindhudurg district of Maharashtra (Umathay 1993).

7. Auriferous placer deposits and beach sands

Gold occurs in India as lode gold, in stratified sulphide deposits, in conglomerates, quartzites, in river placers, in laterite /weathering profile (Radhakrishna and Curtis 1991). Names such as Suvarnarekha, Honnuhole, Suvarnavati, Ponnupuzza which means golden stream indicate that Indian rivers are a great source of alluvial

Table 8. Gold deposits In India

State	Area and Local Geology	Work on gold	References
Uttaranchal	Subgreenschist to greenschist facies Metabasalt, Nainital District	Tiny Au grains in disseminated fashion suggesting widespread hydrothermal activity	Shanker et al. 2002
Assam	Subarnarekha, Subansiri rivers	Placers deposits	Radhakrishna and Curtis 1991
Bihar	1.Cu mines 2.Subarnarekha, Subansiri rivers	1.Association with copper, silver, cobalt 2.Placers deposits	Radhakrishna 2002; Radhakrishna and Curtis 1991
Rajasthan	1.Newania Carbonatite, Udaipur 2. Metalogenic rocks,dolomite-Sanjela-Manpur-Dugocha Belt, Salumber Area, Udaipur 3. Impure/amphibole-bearing marble and dolomite,Bhukia -Kundli 4. Khetri and and Rakha	1.Evidence of Epithermal Activity and Gold Mineralization 2. Gold Mineralisation in Palaeoproterozoic Rocks 3. Forms of fine specks and flakes (0.7 x 0.2mm) 4. Polyrnetallic sulphide deposits	Golani and Pandit 1999; Nandan et al. 2003; Radhakrishna and Curtis 1991
Madhya Pradesh	Malanjkhand	Disseminated Au in intrusive sand volcanics	Radhakrishna and Curtis 1991
Gujarat	Cu mines	Studies on recovery as by-product during refining of copper	Radhakrishna 2002
Orissa	Chromite ore	Occurance in the form of cuprian grain in chromite ore	Rao et al. 2006
Andhra Pradesh	Gadwal Schist Belt	Reported the occurnce in Soil (0.035-4.25); Termite moun (0.025 to 0.07), pegmatite samples (0.035 to 0.25) and metabasalt 0.045 in ppm	Murthy and Bhattacharjee 1997
Maharashtra	1.laterite and powdery ore, Keri and Kalne 2.latcrite and iron ores, Sindhudurg district	1.Association of Au valucs from 0.06 to 0.16 ppm 2.< 0.1 ppm gold	Umathay 1993
Karnataka	1.Kolar 2.Archaean crystallines granites, gneisses, patches of green stones and basic dykes, conglomerate, Bhima Basin 3. Conglomerates, graywacke, banded iron formation (BIFs) and laterite Chitradurga Schist Belt 4. Sericite-chlorite-phyllite/ schist, argillites, greywackes and BIF. Hiriyur formation of Chitradurga Group	1.Lode Au associated with quartz-carbonate veins 2. Occurance of Au in the interstitial spaces of the sand grains as rounded, flattened and dendritic grains, ranging in size from 20 to 200 microns 3. Occurance in sulphidic BIFs ranging from 0.7 to 3.2 g/t 4. Au mineralisation	Radhakrishna and Curtis 1991; George 1995; Sawkar et al. 1995; Madusudan et al. 1994

Table 8. Contd......

State	Area and Local Geology	Work on gold	References
Kerala	1. Metamafic and metaultramafic rocks 2. Nilambur valley	1.Primary Au mineralisation is associated with quartz veins and veinlets intruding the amphibolites, talc- tremolite schists and iron -formations. 2. Association of Au with lateritic forms of rocks	Nair 1993; Radhakrishna and Curtis1991

gold. Occurrence of gold as inclusions in amphiboles, in auriferous quartz in the beach sands of Chavakkad-Ponnani, Kerala Coast has been reported (Nayak, 2011). In the Nilambur Valley of Wynad gold field in southern India, two types of gold -bearing gravels have been identified, the older one which occurs at higher altitude and being richer in Au and the other typein recent gravels (Santosh et al. 1992). Studies have shown the occurrence of both primary grains with jagged grain contours and secondary grains. The morphological, textural and chemical characteristics of gold grains in stream gravels from the Siruvani River in Attappadi Valley, southern India has been reported in detail (Nakagawa et al. 2005). Studies on the placer deposits of Attappadi Valley in southern India have shown the presence of both primary and secondary gold grains, both these forms being differentiated by a marked contrast in microtextures and chemical corrosive cavities (Nakagawa et al. 2005)

8. Gold in laterite

Laterites have developed from Archean to lower Proterozoic gold-rich formations under tropical climates on a "transcontinental "precambrium cratonic belt across the region of Africa, South America, India and Australia (Colin et al. 1997). Long term weathering of granites, gold rich quartz lenses, gneisses has led to the formation of laterites. Biofilm dominated by C.metallidurans were observed on the surface of Au grainsin moderate, sub-tropical and wet-tropical zones in Australia (Reith and McPhail, 2006, 2010). Au grain formation model has been developed that integrates a primary origin with secondary mobilization and aggregation processes (Reith et al. 2010). Investigation of the influence of biogeochemical processes on the transformation of Au in arid environments was done by Fairbrother et al. (2012). In India, Wynad-Nilambur were the earliest gold occurrence to be explored in the states of Tamil Nadu and Kerala. In Nilambur region of south India the occurrence of supergene gold associated with laterite weathering has been reported. The gold grains associated with laterite profiles were reported to be having regular grain contours, rounded faces and also as xenomorphic grains with plane phases. Gold has been recovered from the laterite matrix of gravels in old river terraces and residual laterites (Nair et al. 1987). During weathering the finest gold particles are found migrating 70cm into the saprolites as gold has a density 19.3 g/cm^3 being higher than other imported phases (Colin et al. 1997). Similar work has been reported in Australia on the occurrence of coarse, Ag-rich, primary, angular, secondary gold in saprolite (Anand et al. 2017).

9. Public sector role

9.1 Biomining technique at Hutti Gold Mines, Karnataka

An integrated biotechnological approach to gold processing holds great promise since it is cost-competitive, energy-efficient and environment-friendly. Recently, bio-oxidation of gold ores has been implemented as a commercial process at Hutti Gold Mines, Karnataka and is under study worldwide for further application to refractory gold ores. Biooxidation involves treatment with Acidithiobacillus ferro-oxidans to oxidise the sulphide matrix prior to cyanide extraction (Devasia and Natarajan 2004). Thiobacillus ferrooxidans which is sulphur and iron oxidising, acidophilic autotroph exhibiting bacteria growing at acidic pH of 2 at 350° C has been isolated from the Hutti Gold Mines. These organisms are capable of dissolving sulphides such as pyrite and arsenopyrite with which free gold particles are associated.

A concentrate containing up to 30 gm/ton of gold and 800 gm/ton of silver was subjected to bacterial oxidation capable of liberating the encapsulated gold particles from sulphide minerals which after subsequent cyanidation will yield almost complete extraction of the precious metals.The nominal capacity of the plant is to treat 100 kg/day of flotation concentrate, which can be enhanced to 200 kg/day.

10. Private sector role

10.1 Deccan Gold Mines Ltd. (DGML) and success of gold exploration

Deccan Gold Mines Ltd. (DGML) is the gold exploration company which has been involved in gold exploration activities in the states of Karnataka and Andhra Pradesh. Activities by this company have resulted in defining a number of gold prospects spread across these states and its objective is to advance these gold prospects into commercial gold production. DGML has so far explored an area of around 6,574 sq. kms. in Dharwar Shimoga Greenstone belt, Mangalur Schist Belt, Hutti-Maski Greenstone Belt in the State of Karnataka.

10.2 Contribution of Pebble creek mining limited company in gold exploration

Pebble Creek mining limited company has expertise in core drilling and finding new ore deposits and developing and operating mines to provide the mineral products. This company has set two projects in India, Adi Gold Mining Private Limited and Gadarwara project. The Askot deposit is located at Askot village, Uttarakhand state (formerly part of Uttar Pradesh), in the Himalayan foothills of northern India and has indicated a resource of 1.86 million tonnes containing 2.62% copper, 5.80% zinc, 3.83% lead, 38 grams of silver per tonne and 0.48 grams of gold per tonne and has drilled six more holes in 2010 and added 1.2 million tonnes of inferred resource to the deposit.

11. Problems faced by gold mining industry in India

Due to the rapid increase in the demand for metals worldwide, reserves of high-grade ores are diminishing at an alarming rate and there is a need to excavate new sources of metals. But there are many problems in metal extraction. The problems which come in the way include massive investment in exploration and upgrading of technology, mitigation of environment degradation due to mining and adoption of environment friendly technologies. Due to high energy and capital inputs, the recovery of metals from low and lean grade ores using conventional techniques is also very expensive. In the case of low grade ore bodies, it is very important to remove as much of the desired ore from the mined material as possible so that mining operation remains economically feasible. Miners must not only monitor the incoming material to maximize the extraction process, but the waste material must be monitored just as closely to ensure that none of the valuable minerals are lost. Another major problem in mining industry is environmental cost due to the high level of pollution from these technologies. Mining processes produce large volumes of waste, some of it highly toxic. This waste can result in acid mine drainage and groundwater contamination. Mining companies mainly use cyanide and mercury to extract gold from crushed ores. Very low-grade ore, with minimal residues of gold, is crushed and piled on the ground, then sprayed with a cyanide solution. Use of mercury has led to major public-health problems for miners and communities around mining districts. Despite having some of the best potential ground for gold mineralization, In India,the land of the world famous Kolar Gold Fields and the largest consumer of gold on earth, annual primary gold mine output has reduced significantly to below 5 tonnes.

12. Potential of biomining in India

Gold occurs in multiple geological environments in India, thus there is a huge potential for exploration of gold and biomining in India. Gold occurs in India as lode gold, in stratified sulphide deposits, in conglomerates, quartzites, in river placers, in laterite /weathering profile (Radhakrishna and Curtis 1991). All these available auriferous zones open a huge window to environmental friendly and economical technologies such as biomining. The potential of biomining in India is explained in Fig. 3. Rational sampling and collection of auriferous samples can be carried out from rocks such as Banded Iron Formation (BIF), Banded Magnetite Quartzite (BMQ) mined rejects and non-mining such as beach sand, placer deposits, laterite, termite mounds areas of India. Such

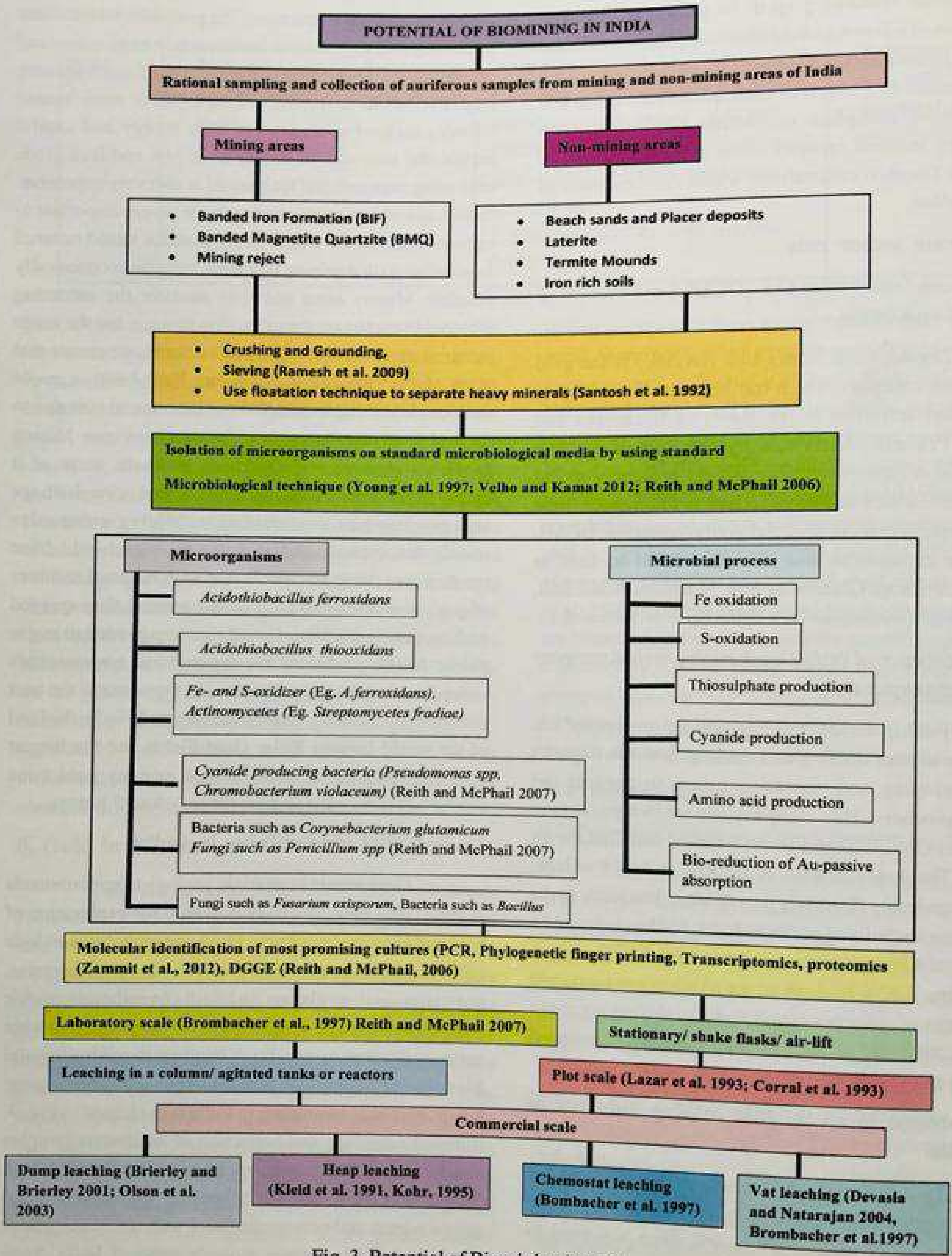

Fig. 3. Potential of Biomining in India

samples can be further crushed and grounded, sieved (Ramesh et al. 2001). Heavy metals can be separated by using floatation technique (Santosh et al. 1992). The samples can be further analysed by ICP-AES, ICP-IES, Fire assay techniques for detection of Au (Anand et al. 2017; Falconer and Craw 2009; Szaloki et al. 1999). Morphological studies and biofilm association can be studied using microscopic techniques such as light microscopy, Phase contrast microscopy, SEM-EDX, TEM (Fairbrother et al. 2012; Reith and McPhail, 2007). Association of microbial biofilms with such auriferous samples (Reith et al. 2016) shows that there is a huge potential for exploration and study of useful unexplored microbiological espects from such auriferous samples. Microrganisms such as acidophiles, Thiobacillus ferroxidans and cyanide producing microbes such as C.Violeceum (Reith and McPhail, 2007) are being used in biomining. Microorganisms are able to mobilize metals through the processes such as formation of organic and inorganic acids, excretion of complexing agents, oxidation and reduction reactions. Generally, sulfuric acid is the main inorganic acid formed in the leaching environment. It is formed by sulfur oxidizing microorganisms such as thiobacilli. Such microorganisms can be isolated from such an environment and can be further used in bio-oxidation and bio-reduction at laboratory scale and further at pilot and commercial scales (Brombacher et al. 1997). Biomining is commercially applied using three different engineered methods which include dump bioleaching, heap bioleaching/biooxidation, and stirred tank bioleaching/ minerals biooxidation. Molecular identification of the most promising cultures can be carried out by PCR, Phytogenetic finger printing, Transcriptomics, proteomics (Zammit et al. 2012), and DGGE (Reith and McPhail, 2006). Once culture is identified, laboratory scale bioleaching (Brombacher et al. 1997) in stationary/ shake flasks conditions can be carried out , followed by pilot scale leaching in columns/agitated tanks or reactors (Lazar et al. 1993; Corral et al. 1993) and further can be applied at a commercial scale by techniques such as Dump leaching (Brierley and Brierley CL, 2001; Olson et al. 2003), Heap leaching (Kleid et al. 1991; Kohr, 1995), Chemostate leaching (Brombacher et al. 1997) and Vat leaching (Devasia and Natarajan 2004; Brombacher et al. 1997).

13. Conclusions

Gold occurs in India as lode gold, in stratified sulphide deposits, in conglomerates, quartzites, in river placers, in laterite /weathering profile (Radhakrishna and Curtis, 1991). All these available auriferous zones open a huge window to environmental friendly and economical technologies such as biomining. Association of microbial biofilms with such auriferous samples (Reith et al. 2016) shows that there is a huge potential for exploration and study of useful unexplored microbiological espects from such auriferous samples. Microrganisms such as acidophiles, Thiobacillus ferroxidans and cyanide producing microbes such as C.Violeceum (Reith and McPhail, 2007) are being used in biomining and such microorganisms can be isolated from such environment and can be further used in bio-oxidation and bio-reduction at a laboratory scale and further at pilot and commercial scales (Brombacher et al. 1997).

Acknowledgements

First author would like to aknowledge NF-OBC UGC scholarship for funding. This work was supported by UGC-SAP Phase III – Biodiversity, ecophysiology, bioprospecting programme and forms part of ongoing work of Goa University Fungus Culture Collection and research unit (GUFCCRU) On mapping microbial biodiversity. We thank R.N.S Bandekar CO, Vasco Da Gama for partial funding.

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Received on 09-08-21; Revised Ms accepted on 22-10-21