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REVIEW ARTICLE

Comparative study of ancient and modern Indian metallurgical practices: evolution and continuity

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Abstract

Metallurgy in the Indian subcontinent presents one of the world's longest and most continuous technological trajectories, extending from the Indus Valley Civilization through medieval high-carbon steels and zinc distillation, to present-day industrial steel, copper, zinc, and gold production. This review synthesizes archaeological, textual, and materials-science evidence to trace the evolution of extractive metallurgy, alloy design, thermomechanical processing, and corrosion management in India. Early phases highlight copper and bronze craftsmanship, followed by the civilizational pivot to bloomery ironmaking during the Vedic period, culminating in advanced Gupta iron exemplified by the Delhi Pillar. Medieval India contributed two globally significant innovations: crucible-derived wootz steel, whose carbide microstructures inspired Damascus blades and modern tool steels, and large-scale downward-distillation zinc smelting at Zawar, which anticipated European methods by several centuries. Gold mining and jewellery traditions reveal continuity between prehistoric extraction and ethnographic practice, with distinctive cultural and ritual significance. The manuscript further connects these ancient practices to modern Indian metallurgy, including the establishment of integrated steel plants, leadership in sponge iron (DRI), hydrometallurgical copper and zinc smelting, and sustainable innovations such as secondary metallurgy, bioleaching, and circular resource use. By interlinking historical achievements with current industrial practice, this review demonstrates how ancient empirical ingenuity continues to resonate in contemporary process design, resource stewardship, and materials engineering. The synthesis not only positions Indian metallurgy within a global comparative frame but also underscores its enduring relevance to modern sustainability and innovation challenges.

Keywords Indian metallurgy · Ancient ironworking · Wootz steel · Corrosion resistance · Metallurgical evolution · Sustainable metallurgy · Industrialization

Introduction

Metallurgy has been a cornerstone of technological progress throughout human history, enabling the production of tools, weapons, and infrastructure that transformed societies. India, with its long and diverse cultural history, stands out as a prime example of metallurgical innovation and continuity. From prehistoric copper smelting to advanced modern steelmaking, Indian metallurgy demonstrates both transformative breakthroughs and the sustained preservation of ancient techniques. Its evolution reflects not only millennia of technological growth but also the blending of traditional craftsmanship, scientific discovery, and socio-economic forces across historical periods (Beit Arieh 1980).

Archaeological evidence places the origins of Indian metallurgy over 3000 years ago, with the Indus Valley

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Civilization (IVC) exhibiting sophisticated practices in copper, bronze, lead, gold, and silver working. Finds from Harappa, Mohenjo-daro, Lothal, Rangpur, and Dholavira confirm smelting and finishing technologies (Tylecote 1992). These early metallurgists established the foundations for India's metallurgical dominance, later amplified by the mastery of iron. The transition to ironworking marked a significant milestone in global metallurgical development. Iconic examples include the Delhi Iron Pillar (c. 400 CE, Gupta period), which has survived for over 1,600 years with minimal corrosion due to its high phosphorus content, and the iron beams of the Konark Sun Temple, which illustrate advanced control over smelting and forging. Equally significant is the celebrated wootz steel, exported widely to the Middle East and Europe, where it was fashioned into Damascus blades. Together, these achievements highlight India's advanced understanding of alloying, bloomery furnaces, and solid-state reduction (Beck 1976). Beyond technological feats, metallurgy in India carried strong cultural and spiritual dimensions. Metals were integral to religious rituals, sculptures, coinage, and architecture. The techniques employed were often informed by philosophical and spiritual traditions, demonstrating the close integration of material knowledge and cultural identity.

Table 1 Summary of metallurgical developments from the Indus Valley Civilization to the Late Medieval Period

Period	Timeline	Key metallurgical developments	Significance
Indus Valley Civilization (IVC)	c. 3300–1300 BCE	Use of copper; techniques like casting, smelting, and alloying; creation of bronze by mixing copper and tin	Early foundations of metallurgy; advanced urban craftsmanship
Post-Indus & vedic age	c. 1900–500 BCE	Transition from copper to iron; discovery of iron artifacts from ~ 1200 BCE; emergence of iron smelting	Iron tools revolutionized agriculture and warfare
Mauryan & post-mauryan periods	c. 322 BCE–300 CE	High-quality iron production; Delhi Iron Pillar made of corrosion-resistant wrought iron; development of carburizing techniques	Significant advancement in iron durability and processing
Gupta period	c. 300–550 CE	Skilled blacksmiths; high phosphorus iron artifacts; discovery of major iron smelting sites in central India	Noted for corrosion-resistant and durable iron
Medieval period	c. 600–1200 CE	Development of wootz steel with high carbon content; exported internationally for its sharpness and strength	Marked global recognition of Indian steel
Mughal era	c. 1526–1857 CE	New techniques introduced; production of weapons and decorative artifacts; Thanjavur cannon (seventeenth century) is a major example	Blend of art and functionality in metalwork
Colonial period	c. 1757–1947 CE	Decline of traditional practices due to British industrialization; increased scholarly study of ancient metallurgy	Knowledge preserved through academic efforts

The 16th–eighteenth centuries did not represent an immediate technological decline, as indigenous smelting and wootz ingot exports to Persia and the Middle East remained active well into the 18th–nineteenth centuries, with centers such as Ghattihosahalli maintaining production. The eventual contraction of artisanal iron and crucible-steel industries was primarily driven by colonial economic and forestry policies especially the Forest Acts restricting charcoal supplies and the influx of cheaper imported metals, rather than technological shortcomings (Jaikishan et al. 2021). Indigenous bloomery ironworking persisted into the nineteenth century. Industrial ironmaking began with pig iron at Kulti (Bengal Iron Works) in the 1870s, followed by the Jamshedpur blast furnace of TISCO in 1911, which marked the birth of India's modern steel industry. Post-independence, India's metallurgical sector experienced rapid growth, led by large-scale plants such as Tata Steel, expanded mining operations, and the adoption of modern technologies including electric arc furnaces, induction furnaces, and continuous casting. Today, India's metallurgical capacity spans steel, non-ferrous alloys, and advanced castings, while also integrating sustainability-oriented innovations.

Despite the disruptions of colonialism and industrialization, Indian metallurgy demonstrates a remarkable continuity. Ancient practices, such as the high-phosphorus iron of the Delhi Pillar, inform modern corrosion-resistant alloy design, while studies of ancient wootz steel inspire contemporary research on ultra-high-carbon steels. Investigations into the microstructures and processing routes of ancient artifacts continue to provide insights into sustainable metallurgical practices with direct relevance for modern industries, including low-carbon steelmaking and circular economy approaches (Bennett 1989). Importantly, India's metallurgical heritage persists not only in large-scale industry but also in small-scale and artisanal practices. Craft communities maintain techniques reminiscent of traditional crucible steelmaking, while cultural legacies of bronze casting (e.g., the Chola bronzes) remain celebrated. Thus, the study of Indian metallurgical traditions provides both a historical lens on ancient civilizations and a source of lessons for addressing contemporary challenges in sustainable production, resource efficiency, and innovation. (Tables 1 and 2)

This paper seeks to examine the continuum between ancient and modern Indian metallurgical practices, comparing materials, processes, and socio-economic contexts. By

Table 2 Chronology of the copper bioleaching process

Era	Advancements in the copper bioleaching process
1000 B.C	Cu recovery from mine waters in the Mediterranean region and China has been achieved without utilizing the bioleaching process
177–122 B.C	Cu cementation process
23–79 A.D	Cu minerals were extracted through a leaching process
166 A.D	The scientist Galen recorded the use of the in situ leaching method at an ancient copper and lead mine in Cyprus
10th Centaury	The Chinese pioneered the commercial extraction of Cu from $CuSO_4$ using the cementation process
1086	The Gall ($CuSO_4$) process outlined the commercial method of Cu leaching and recovery through cementation on iron, with the resulting Cu being utilized for coinage
1096	The Chiangshan cementation plant had an annual production capacity of 190 tons of copper per year
1494–1555	A German scholar, Georgius Agricola, detailed techniques for extracting Cu by leaching Cu-containing ores. He also explained the process of roasting pyrite to facilitate leaching and produce $FeSO_4$
1572	Industrial-scale heap leaching of copper sulfides was carried out at Rio Tinto in Spain
1879–1896	At Rio Tinto, bioleaching of low-grade ore was implemented using heaps of low-grade Cu ore (0.75% Cu) stacked to a height of 10 m and left for 1 to 3 years to undergo "natural" decomposition. Approximately 20–25% of the Cu remaining in the heaps was recovered yearly. It is estimated that around 200,000 tons of ore were bio-leached between 1879 and 1896
1900–1920	Commercial Cu production was achieved through leaching and Cu cementation in Butte, MT, USA; in situ leaching was conducted in Cananea, Sonora, Mexico; and Cu was recovered from underground mine water in Bisbee, AZ, USA
1921–1940	Large-scale dump leaching of open pit waste rock was conducted with the recirculation of leach solutions
1950	A Cu bio-dump leaching process was developed to extract copper from low-grade sulfide ore
1960	The first industrial-scale bio-heap leach process was implemented
1961	Although industrial leaching had been practiced at Rio Tinto mines for decades, the involvement of bacteria in copper solubilization was confirmed in 1961 with the discovery of *Acidithiobacillus ferrooxidans* in the leachates
1995	The bioleaching of chalcopyrite concentrate was developed and evaluated on a commercial scale
2003	M/S BHP showcased the use of acidophilic iron-oxidizing archaea to bioleaching chalcopyrite concentrate in stirred bioreactors, facilitating the commercial extraction of copper and gold
2023	Approximately 40 industrial-scale bioheap and bio-dump leaching processes operate in various countries worldwide

tracing these trajectories, we highlight how past traditions shaped industrial developments and continue to inspire modern practices, underscoring the enduring legacy and relevance of India's metallurgical heritage in the twenty-first century (Thornton 2009).

Historical context of ancient Indian metallurgy

Ancient Indian metallurgy shows a sustained arc of innovation from the Early Bronze Age through the Late Medieval period. Through iterative experimentation and empirical optimization, metalworkers developed a practical command of extractive processes, alloy control, thermomechanical treatments, and corrosion management for iron, copper, bronze, and zinc. These technologies also carried cultural and economic weight—metals signified ritual value, state power, and artisanal skill. The evolution can be traced across distinct phases, each marked by characteristic furnace types, alloys, and artifact classes.

Early iron age metallurgy (c. 1900–500 BCE; securely attested by ~ 1200 BCE)

Technological foundations and practice: Indigenous smelting traditions sustained in part by communities such as the Agarias centered on the bloomery: iron ore reduced with charcoal in small clay shaft furnaces fitted with tuyeres for forced air. The porous iron bloom, interspersed with slag, was consolidated by repeated reheating and hammering. Archaeological evidence from sites such as Naikund (c. 700 BCE), coupled with ethnographic documentation, demonstrates careful control of furnace geometry, charge preparation, air delivery, and slag management, with adaptations to local ore and fuel ecologies. Resource-sensitive choices seasonal smelting cycles and controlled charcoal use embedded metallurgy within broader environmental and social systems; ironmaking underwrote livelihoods and identity within these communities (Haerinck 2021).

Macro-transition from copper/bronze to iron: During the Post-Indus and Vedic periods, iron's abundance, hardness, and edge retention enabled decisive gains in agriculture, urban growth, and military capability. While copper alloys remained important, tin scarcity constrained large-scale bronze; iron ores across central/eastern India were more accessible but demanded higher temperatures and tighter redox control. By ~ 1200 BCE, securely dated artifacts attest to successful smelting. The transition was not a mere material substitution but a process-engineering leap: once bloomery control stabilized, iron rapidly became the dominant tooling and construction metal across the subcontinent.

Metallurgy in the Gupta period (c. 300–550 CE)

Compositional/process control and corrosion resistance: A hallmark of Gupta metallurgy is the Delhi Iron Pillar—over seven meters tall and nearly six tons—renowned for exceptional atmospheric corrosion resistance over ~ 1,600 years. The pillar comprises nearly pure wrought iron with elevated phosphorus and very low S/Mn, favoring gradual formation of a phosphate-bearing passive film (often described as an iron hydrogen phosphate hydrate) that inhibits further oxidation. Unlike modern stainless steels (Cr/Ni-alloyed), Gupta ironworkers—guided by empirical practice—arrived at compositions and processing routes that conferred long-term stability.

Broader practice and organization: Excavations in central India reveal large smelting locales, indicating organized production. Forging quality improved via efficient slag removal and careful thermomechanical sequencing, extending tool and structural lifetimes. Frequent deliberate or incidental use of high-phosphorus irons contributed to durability. Inscriptions and textual evidence point to metalworking guilds that regulated standards, sustaining compositional and processing consistency. The pillar and allied finds exemplify practically informed process control, prefiguring later Indian expertise in corrosion management.

Medieval metallurgical achievements: wootz (crucible) steel production

Significance of wootz steel

Wootz is a crucible-made, hypereutectoid steel produced in South Asia and famed internationally (Middle East, Europe) via blade manufacture commonly referred to as "Damascus." Contemporary accounts (e.g., Tavernier, Buchanan) document vibrant export centers in regions such as Golconda, parts of Mysore, and Andhra. The steel's value derived from both mechanical performance (edge retention, wear resistance) and distinctive appearance, which underpinned extensive trade and artisanal prestige.

Extraction and manufacturing techniques

Production (see Fig. 1) used sealed clay crucibles charged with refined wrought iron (or sponge iron) and carbonaceous matter (plant materials). Crucibles were heated intensely in charcoal-fired furnaces with bellows, achieving elevated temperatures and a carbon-rich environment. The sealed system limited oxidation and enabled controlled carbon uptake, yielding high-carbon ingots suitable for forging. Local fine clays and well-prepared crucible mixes were critical for thermal shock resistance and metallurgical cleanliness.

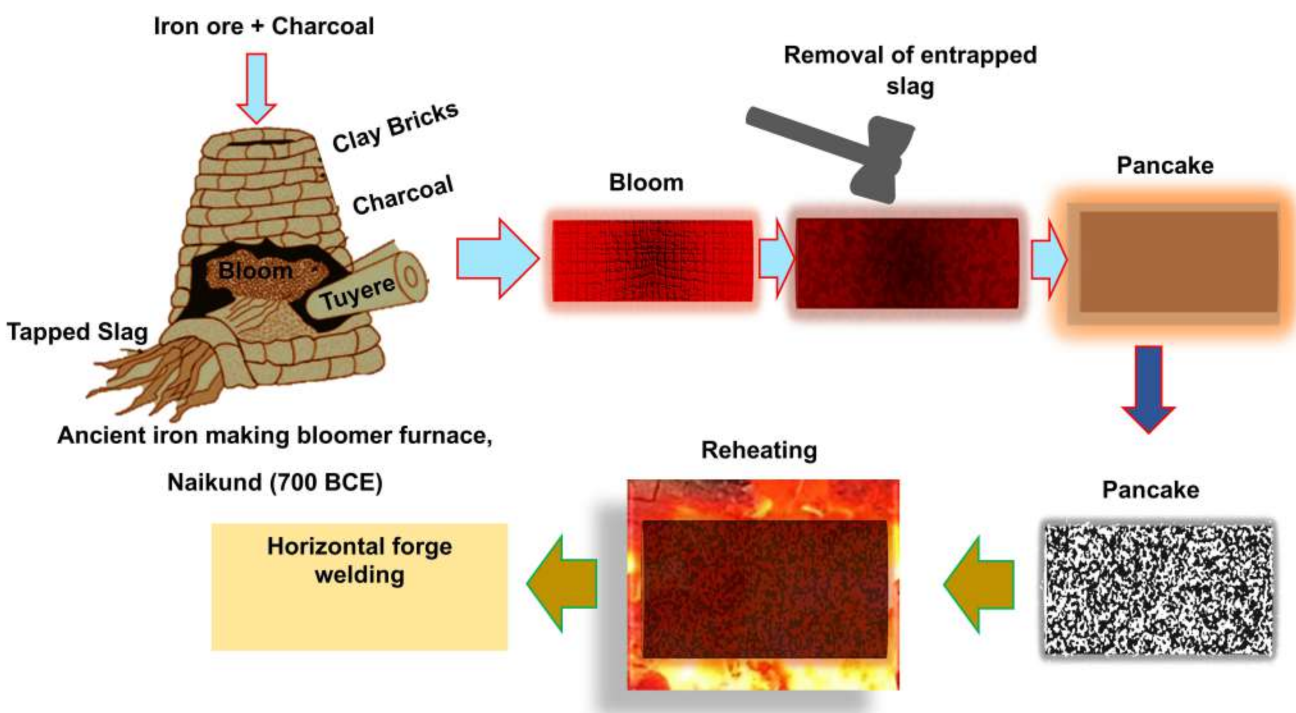

Fig. 1 Schematic representation of the ancient Wootz steel manufacturing process. Starting from raw material preparation to crucible melting and forging, each stage is illustrated to emphasize the traditional metallurgical innovations (Harper 1992)

Process features wootz steel production

The crucible route achieves uniform carbon distribution (typically ~ 1.0–1.5 wt% C). Slow post-melt cooling and specific thermomechanical schedules favor development of carbide (cementite) arrays responsible for the characteristic "watering" (Damascus) pattern. Subsequent forging refines the structure and properties. (Note: pattern generation in classical Damascus is linked to crucible metallurgy and processing history rather than extensive martensitic transformation.)

Steps used in wootz steel production

Refining of feed iron → batching with carbon source → crucible sealing → high-temperature firing with regulated air → slow cooling/ingot extraction → forging/thermal cycling to tune carbide arrays and toughness → final heat treatments, where quenching was applied in later steps, tempering followed to balance hardness and toughness.)

Metallography and microstructure of wootz steel

Wootz typically shows 1.0–1.6 wt% C, with cementite arrays within pearlitic/ferritic matrices giving the "watered silk" appearance. Carbide morphology and distribution depend on ingot solidification and subsequent thermal cycling. Reports of phosphorus, Mn, or Si reflect ore/charcoal sources and do not by themselves define the watering. Martensite may be locally present after edge quenching, but the canonical Damascus patterns arise from cementite arrays, not from a predominantly martensitic bulk.

Tradet and Economic Impact

Seventeenth-century sources report premium pricing and large volumes of ingot exports from south India to West Asian markets. Patronage (e.g., Mysore) fostered workshops whose blades became synonymous with quality. European attempts to replicate wootz spurred systematic studies of high-carbon steels and heat treatment, influencing later metallurgical science.

Contraction and colonial impact

Artisanal crucible-steel production contracted not primarily for technical reasons, but due to colonial Forest Acts (restricting charcoal), changing market structures, and import competition. Disarmament and workshop disruption after 1857 further accelerated decline, even as industrial steelmaking rose elsewhere.

Continuities and relevance

Ancient practice underscores resource-aware processing, microstructural design via thermal cycles, and performance-driven forging. Insights from wootz especially carbide control continue to inform modern alloy/heat-treatment strategies and inspire comparative studies in ultra-high-carbon steels.

Cross-cutting ancient practices and technical themes

Chronological synthesis (3000 BCE–1000 CE)

IVC artisans developed copper alloying and casting, establishing durable craft traditions. Ironmaking expanded in the Mauryan and later periods; by the Gupta era, compositional/processing controls produced corrosion-resistant irons (e.g., Delhi Iron Pillar, c. 400 CE). Wootz crucible steels achieved international renown. The Zawar zinc industry (Rajasthan) perfected downward distillation by the medieval period, enabling large-scale brass centuries before parallel European developments.

Extractive metallurgy

Solid-state reduction (bloomery) dominated ancient ironmaking—ore + charcoal → bloom → consolidation by forging. In non-ferrous metallurgy, zinc distillation innovations at Zawar (≥ 12th c. CE) enabled metallic zinc and influenced later brass technologies. (Modern DRI echoes the solid-state reduction principle.)

Alloying techniques and compositions

Bronze and brass were widespread in weaponry, currency, sculpture. Zawar's mastery of zinc distillation produced high-zinc brasses, while wootz showcased control of carbon and carbides—insights still pertinent to advanced tool steels.

Thermomechanical and casting practice

Blacksmiths applied quenching/tempering to adjust hardness and toughness of steels; cold working/polishing refined sculpture and tools. Lost-wax casting (cire perdue) flourished from IVC figurines to Chola bronzes, demonstrating precise control of mold investment and cooling.

Corrosion management strategies

High-phosphorus irons (e.g., Delhi Pillar) formed protective phosphate films, conferring exceptional atmospheric durability. Early coating strategies (e.g., lead-bearing surfaces noted at other pillars) suggest empirical galvanic protection. These ideas resonate with modern weathering steels and sacrificial anodes.

From past to present

Continuities link extractive routes (solid-state reduction ↔ DRI), alloy design (Cu–Sn, Cu–Zn ↔ engineered brasses/bronzes), thermomechanical control (forging/heat treatment), and corrosion strategies (phosphorus-aided stability ↔ contemporary surface engineering). This lineage informs today's structural and tool steels and supports sectors from construction to transport—while highlighting sustainability lessons inherent in low-waste, locally adapted ancient practices.

Copper metallurgy (South Asia in old-world context)

South Asian practice: Copper (Cu) was among the earliest metals used for tools and artifacts. The smelting and casting of copper in South Asia are well documented from the pre-IVC/IVC through later periods. Early copper mining/smelting sites occur in Rajasthan's Khetri belt and elsewhere. Typical small shaft furnaces (≈35 cm tall; rim ≈20 cm; base ≈10 cm) used charcoal with roasted ore + crushed quartz (flux) charged as small lumps. Quartz helped separate Fe-bearing slag from Cu; the denser copper collected at the base, with slag tapped off. Ingots (often "bun" shaped) were extracted by dismantling the furnace bottom. Archaeological remains show furnaces set on brick platforms with earthen packing to retain heat (Fig. 2). Beyond South Asia, comparative sequences on the Iranian plateau and northern Euphrates show cold/heat hammering → annealing → casting → crucible smelting (Gandhi 2014). These comparisons contextualize South Asian developments without overstating cross-regional synchrony.

Comparative sequences: Comparative old-World sequences (Iranian Plateau, northern Euphrates) show similar progressions: exploitation of native copper and pigments (e.g., malachite), early cold/heat hammering and annealing, followed by casting and then crucible-assisted smelting as temperatures and reaction control improved. These parallels underscore convergent solutions to common extractive challenges.

Bronze-making: processes, regions, and typologies

Origins and spread: Early "bronze" included arsenical copper (often incidental). Deliberate tin bronze (Cu–Sn) appears in Mesopotamia and western Iran by the late 4th–early 3rd millennium BCE, becoming dominant by the mid-3rd millennium BCE (Fleming et al. 2005; Nezafati et al. 2006; Patro et al. 2025; Pigott et al. 2003). In Iran (Luristan), direct mixing of local Cu/Sn ores is attested (Kalleh Nissar). Bronze predominated in the Iron Age across western/northwestern Iran; major centers such as Mar lik yielded substantial bronze assemblages (Fig. 3). The Elamite corpus (e.g., Queen Napir-Asu, Fig. 4; Sit-Shamshi, Fig. 5) demonstrates high-fidelity casting (Oudbashi et al. 2012; Lapxérouse and Jean-François. 2014; Harper 1992).

South and East Asia: In China, copper/bronze/brass/arsenical copper are attested from the 5th–4th millennium BCE. In South India, the Chola bronzes (10th-century Thanjavur, Fig. 6) represent pinnacle lost-wax craftsmanship (mostly solid cast; many SE Asian pieces hollow cast) (Datta et al. 2008; Srinivasan and Ranganathan 2006). In eastern India, Tilpi provides early high-tin bronze foundry evidence; Pandu Rajar Dhibi (Period IIA) yields bronzes, Black-and-Red Ware, and microliths (Fig. 7)(Chattopadhayay 2017).

Casting technology (process control): Lost-wax begins with a wax model invested in layered clays; furnace heating drains wax; molten bronze fills the cavity; cooling/

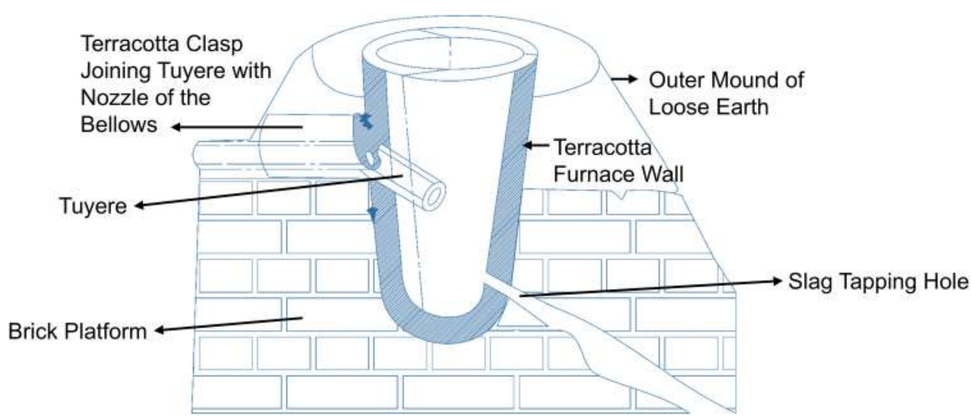

Fig. 2 Schematic of the Aravalli copper smelting furnace, showing the terracotta-lined shaft with tuyère attachment and slag-tapping provision. The design illustrates indigenous metallurgical practices, where natural draft and simple construction materials enabled efficient copper extraction. (Gandhi 2014)

Fig. 3 Two bronze artifacts from the Marlik graves: a spouted vessel with lion reliefs (left) and a sculpted deer statue (right) (Oudbashi et al. 2012), reflecting the metallurgical skill and cultural symbolism of the era

consolidation follows. Hollow casting uses wax shell over a core; wall thickness is governed by wax thickness. Armatures/chaplets (often iron wire) stabilize cores; runners/risers manage flow and shrinkage. Sand casting expands throughput for standard geometries. Crucibles (local clays + fibers) are fired in charcoal hearths (hand/foot bellows); alloy quality is verified by high-T hammering and visual criteria.

Industrial era shifts: Mechanization introduced cupola/reverberatory furnaces, regenerative heating, and flux-assisted refining (e.g., limestone), improving thermal efficiency and alloy cleanliness. Gunmetal (~Cu 88–Sn 10–Zn 2) and other engineered bronzes targeted specific tribological/corrosion needs. Bronze diversified into machinery components (gears/valves/bearings) while retaining artistic/ritual roles.

Zinc metallurgy in ancient India

India occupies a unique place in the history of metallurgy for pioneering the production of metallic zinc and high-zinc brass well before such technologies became established elsewhere. Zinc is notoriously difficult to smelt because its boiling point (907 °C) is lower than the temperatures required for ore reduction, which means it vaporizes and readily re-oxidizes during extraction. Overcoming this challenge required innovative furnace designs and condensation techniques.

The earliest firm archaeological evidence comes from the Zawar region of Rajasthan, where semi-industrial scale zinc smelting was carried out by at least the twelfth century CE. The Zawar furnaces employed a downward distillation technique. Aubergine-shaped clay retorts were charged with zinc ore, sealed, and inserted through perforated plates into furnaces. On heating, zinc vapors traveled downward through stems into a cooler chamber where they condensed into liquid metal that was collected in vessels. This ingenious arrangement prevented re-oxidation and represents one of the earliest known distillation systems for metals (Srinivasan 2016). Textual sources corroborate this technological knowledge. Sanskrit alchemical works such as Rasaratnākara (attributed to Nāgārjuna, ca. 2nd c. CE) and later texts like Rasaratnasamuccaya (13th–14th c. CE) describe processes resembling downward distillation (tiryakpātana) of zinc ores, with references to brinjal-shaped crucibles strikingly similar to Zawar retorts. The production of brass through cementation — heating copper with calamine (Zn ore) — is also explicitly mentioned.

Archaeometallurgical analyses confirm early use of brass with high zinc contents (> 34%), which suggests direct alloying with metallic zinc rather than cementation alone. Finds from Taxila (4th c. BCE) include brass objects with ~ 34% zinc, and a metallic zinc ingot with Brāhmī inscription (ca. 5th c. CE) indicates deliberate production. Later, zinc alloys were widely employed in Hindu, Buddhist, and Jain votive bronzes, and in Bidri ware from Bidar (Karnataka), which

Fig. 4 Bronze statue dated to the fourteenth century BCE, depicting a finely detailed garment and posture. The craftsmanship reflects the advanced metallurgical techniques and artistic traditions of the period (Lapxérouse and Jean-François. 2014)

Fig. 5 Bronze statue of Sit-Shamshi from the fourteenth century BCE, notable for its detailed craftsmanship and representation of contemporary artistic and metallurgical traditions (Srinivasan and Ranganathan 2006)

used high-zinc alloys patinated to a black finish and inlaid with silver. Zinc alloys were also crucial in precision instruments such as brass astrolabes crafted in Lahore in the 16th–seventeenth centuries. Thus, ancient Indian metallurgists

Fig. 6 Bronze Nataraja icon of the Chola period, exemplifying the fusion of metallurgical excellence and symbolic artistry characteristic of South Indian bronze sculpture (Srinivasan and Ranganathan 2006)

Fig. 7 Bronze fish artifact, reflecting symbolic artistry and skilled metal casting techniques of the period (Chattopadhayay 2017)

developed a sophisticated and pioneering tradition of zinc extraction and brass production, combining empirical innovation with codified knowledge, centuries before comparable methods appeared in Europe.

Gold metallurgy in ancient India

Gold use in the Indian subcontinent dates back to the 3rd millennium BCE, with evidence of mining, panning, and jewellery production across several regions. Archaeological surveys in Karnataka's Hutti–Maski belt reveal extensive ancient workings, including shafts over 200 m deep, carbon-dated to the mid-fourth century BCE- among the deepest hard-rock gold mines of antiquity. Ethnoarchaeological accounts suggest continuity of techniques: local communities practiced seasonal alluvial gold panning after monsoon floods, concentrating heavy gold particles by ground-sluicing and amalgamating fine specks with mercury.

The Nilgiris present another significant locus of ancient gold working. Burial cairns in this region (1st millennium BCE) yielded an extraordinary assemblage of gold ornaments alongside high-tin bronze vessels. Techniques such as granulation- fusing tiny gold spheres onto surfaces reveal links to wider Hellenistic traditions but were locally adapted into distinctive regional styles. Earrings, pendants, and diadems show naturalistic motifs such as peepul leaves, crescent moons, and spiked fruits, resonating with imagery from Sangam poetry (1st c. BCE–3rd c. CE). While some scholars speculated on imports, stylistic and technological traits strongly support localized metallurgical traditions.

Alluvial and hard-rock deposits in the Wayanad–Nilgiri–Gudalur belt continued to be exploited into recent times by indigenous groups such as the Kurumbas, who employed wooden pans for stream panning and mercury amalgamation to recover trace gold. These practices mirror ancient small-scale extraction methods, underscoring continuity between prehistoric and ethnographic contexts.

The cultural significance of gold in South India extended beyond ornamentation. Its combination with high-tin bronze vessels in burials suggests symbolic roles in funerary rituals. More broadly, gold metallurgy in ancient India exemplified both technological ingenuity in deep-shaft and placer mining, and artistic innovation in jewellery design, reflecting cross-cultural influences while maintaining distinctive local expressions.

Modern Indian metallurgical practices

Evolution of techniques in India

The trajectory of Indian metallurgy from the late-colonial period to the present reflects rapid industrialization, process intensification, and growing emphasis on environmental performance. A concise timeline:

- Late-colonial foundations. Artisanal iron and crucible-steel (wootz) persisted locally into the 18th–nineteenth centuries. Industrial ironmaking began with Kulti (Bengal Iron Works, 1870s) and reached a decisive milestone when TISCO's Jamshedpur blast furnace was blown-in on 2 December 1911 (steel tapped in early 1912).
- Post-independence expansion (1950s–1980s). Integrated plants and mining expanded (e.g., public sector steel, beneficiation, sinter and pellet plants). The LD/BOF route became standard for hot metal refining, while electric arc/induction furnaces (EAF/IF) anchored a fast-growing secondary steel sector.
- Direct reduction leadership (1990s–present). Abundant iron ore, constrained coking coal, and distributed power catalyzed the DRI (sponge-iron) route, today a defining feature of India's steel landscape and a direct technological echo of ancient solid-state reduction.
- Non-ferrous consolidation. Historic ore provinces transitioned into modern firms: Hindustan Copper Ltd. (Khetri), Hindustan Zinc Ltd. (Zawar/Udaipur), and continued operation at Hutti Gold Mines, linking ancient lodes to contemporary hydrometallurgy and electrorefining.
- Contemporary practice. Continuous casting, secondary metallurgy (ladle refining, vacuum treatment), thin-slab casting/rolling, and pellet-DRI-EAF chains now dominate capacity addition. Industry integrates energy recovery, waste valorization, and circularity (scrap policy, slag as cementitious material, red-mud/gypsum valorization where feasible).

Inception of iron smelting

The first reduction of iron oxide was most likely accidental, discovered when ores were heated with charcoal in simple furnaces. Early metallurgists—serving simultaneously as miners, smelters, and craftsmen—recognized that metallic iron could be produced by direct reduction. An Egyptian tomb illustration (~ 1500 BCE) depicts such an operation, where workers use foot-operated bellows to intensify the fire (Fig. 8) (Habashi 2005). For nearly 3,000 years, this direct reduction method remained fundamentally unchanged. The product, a porous iron sponge or bloom, was consolidated into wrought iron by reheating and hammering to expel slag.

Bloomery ironmaking

The bloomery furnace, the dominant ironmaking technology for almost two millennia, consisted of a small shaft (≈300 mm diameter, 1 m height) built from clay and brick. Charcoal and iron ore were layered, with air introduced through tuyeres connected to bellows. Combustion gases reduced the ore, producing a bloom surrounded by slag. The casing was broken open, and the bloom was repeatedly reheated and hammered to improve purity and forgeability (Fig. 9). Alternative designs, such as beehive furnaces, employed a clay dome sealed over alternating layers of ore and charcoal. After smelting, the dome collapsed and the bloom was retrieved. While effective, these furnaces were small, batch-based, and inefficient, requiring reconstruction after each cycle.

Fig. 8 Egyptian tomb illustration portraying iron smelting, where workers are shown operating bellows and tending the furnace. This depiction provides valuable insight into early metallurgical practices in the ancient world (Habashi 2005)

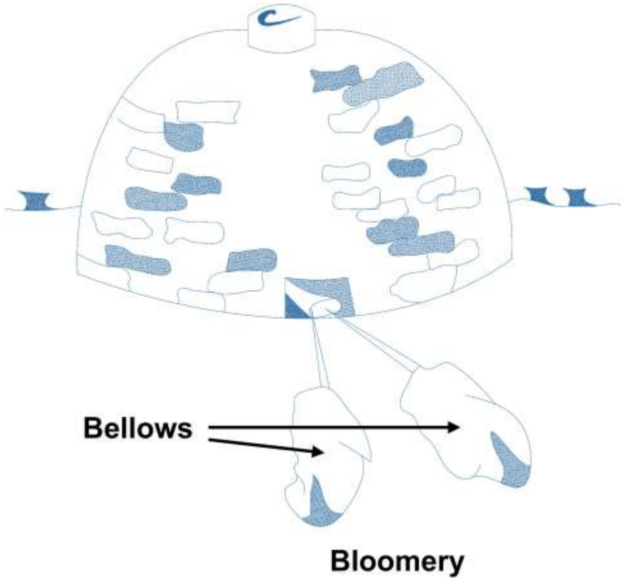

Fig. 9 Schematic illustration of the bloomery process of iron making, showing the furnace structure with bellows supplying air into the hearth. This primitive yet effective method produced a spongy mass of iron (bloom) and represents one of the earliest techniques of iron smelting (Seely 1981)

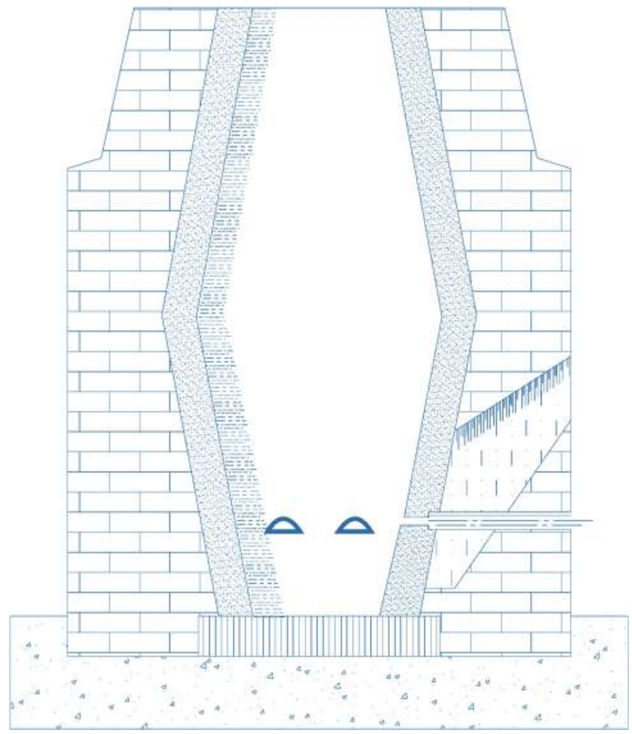

Fig. 10 Cross-section of the Stuckofen furnace, an early European shaft furnace design for iron smelting. The structure highlights the tuyère placement, internal lining, and overall geometry that enabled higher temperatures and more efficient bloom production (Seely 1981)

European advances: catalan forge and stückofen

By the eighth century CE, significant improvements emerged in Catalonia (Spain), where the Catalan forge introduced higher productivity. Stone hearths with water-powered bellows or trompes allowed continuous air blast at greater pressures, enabling blooms up to 160 kg—far surpassing earlier methods. Taller hearths with preheating of charge materials increased efficiency, and the design spread widely across Europe. By the fourteenth century, these developments led to the Stückofen furnace, a tall shaft (~4.8 m) built from stone and clay with multiple tuyeres. Operating at higher temperatures and longer times, the Stückofen produced much larger blooms (~300 kg annually 100–150 tons). A by-product was liquid cast iron—brittle yet significant, as it represented the precursor to modern blast furnaces (Fig. 10) (Seely 1981).

Transition to the blast furnace

The charcoal blast furnace was the logical next stage: a tall, narrow shaft charged from the top with ore and charcoal, with tuyeres near the base blowing hot air. Rising gases reduced the ore; molten iron and slag collected at the bottom. Pig iron was cast into molds or used for foundry purposes. By the seventeenth century, however, heavy demand for charcoal led to severe deforestation in Europe. The breakthrough came in 1709, when Abraham Darby successfully used coke instead of charcoal in a blast furnace. Coke was stronger, cheaper, and available in larger quantities, enabling taller furnaces, higher thermal efficiency, and the mass production of affordable pig iron (Tylecote 1977). In 1828, James Neilson's hot-blast invention further revolutionized the process by preheating the air blast, reducing fuel consumption by ~25% (Gale 1967). Later, recovered top gas was reused for stoves and power, with hot-stove temperatures exceeding 1273 K, significantly boosting energy efficiency.

Evolution of modern blast furnace and sustainability

Modern Indian blast furnaces mirror global practice: tall fire-brick-lined shafts enclosed in gas-tight steel shells, charged with sinter/pellets, coke, and fluxes; hot blast from stoves is oxygen-enriched and often supplemented by pulverized coal injection (PCI). Top-gas recovery generates power and preheats stoves, while continuous casting downstream improves yield and product quality (Fig. 11) (Bashforth 1957; Asanuma et al. 2000; Stoughton 1923). Sustainability pressures now drive Indian steelmakers to explore H_2-enriched reduction, biomass-char injectants, and aggressive scrap recycling. Secondary metallurgy (ladle refining, RH/VD) ensures clean steels for automotive, rail, and infrastructure. Non-ferrous metallurgy has also expanded: HCL in copper (Khetri), HZL in zinc (Rajasthan, building on Zawar's heritage), and Hutti in gold sustain traditions of resource utilization, now underpinned by ESG frameworks.

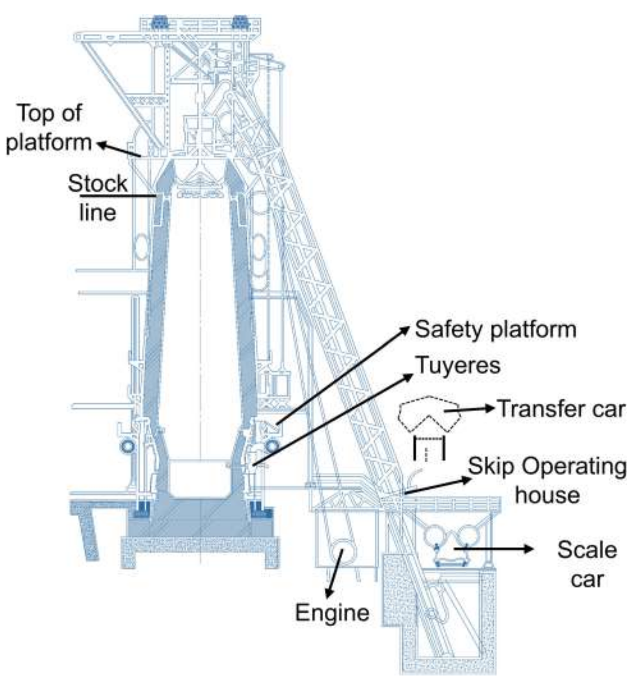

Fig. 11 Schematic cross-section of a blast furnace equipped with a two-bell top charging system and rotating distributor. The design enabled controlled charging of raw materials and efficient gas flow management, marking a key advancement in modern blast furnace technology (Stoughton 1923)

Contemporary metallurgical innovations: advancements in steel production

From bloomeries to early furnaces

In antiquity, steel production relied on direct reduction of iron ore in small bloomeries, with charcoal serving as both reducing agent and fuel. Air blasts facilitated the reduction, producing solid low-carbon iron or steel that blacksmiths could carburize and forge. Production remained small-scale and costly (Tylecote 1984).

By the end of the Medieval period, the blast furnace appeared, producing liquid, carbon-rich pig iron. However, this iron was too brittle for forging. Without effective decarburization, smiths resorted to charcoal-based refining hearths, which were inefficient. The best-quality steels still came from traditional bloomery reduction.

Industrial revolution processes: puddling and crucibles

The eighteenth century brought decisive innovations.

- Puddling furnace (Fig. 12): a coal- or coke-fired reverberatory furnace where pig iron was melted and decarburized by manual stirring with a "puddling bar." This yielded wrought iron more rapidly and with less fuel.
- Crucible process (Fig. 13): small clay/graphite crucibles were charged with pig iron, iron oxide, and flux, then heated with coke to produce high-quality steel ingots. Although slow (≈6 h per batch), it allowed greater control over composition and uniformity.

The converter age: bessemer and open-hearth steelmaking

The breakthrough in mass steel production came with Henry Bessemer's converter (1856, Fig. 14). In this pear-shaped vessel, air was blown through bottom tuyeres, oxidizing C and Si in minutes (Bessemer 1905). The exothermic reactions maintained the melt temperature. However, the acid silica lining limited the process to low-phosphorus ores. The problem was solved in 1879 by S.G. Thomas and P.C. Gilchrist, who introduced a basic doloma lining, enabling treatment of high-P ores (Barracglough 1990; Holappa 2019). In parallel, the Siemens–Martin open-hearth furnace (1860s, Fig. 15) used regenerative heating of fuel and air, melting pig iron and scrap in a reverberatory hearth. Scrap

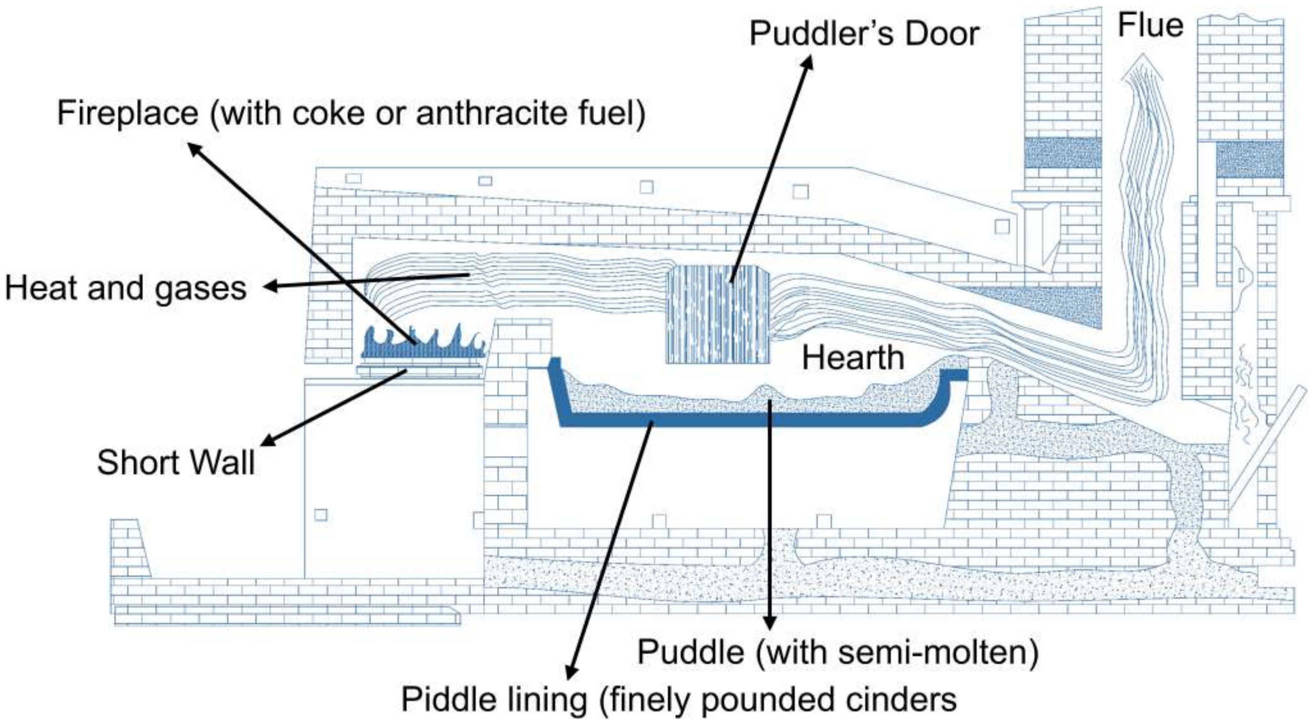

Fig. 12 Diagram of a puddling furnace used in wrought iron production. The figure illustrates the working hearth, fire chamber, and the use of a puddling bar to stir molten pig iron. This manual stirring process helped remove impurities and decarburize the metal, representing a major step in early steelmaking technology

Fig. 13 Illustration of the crucible process for steelmaking. A worker is shown manipulating molten steel within a ceramic crucible using long tongs, demonstrating one of the earliest controlled methods of producing high-quality steel through localized melting and refining (Holappa 2019)

ratio flexibility and slower refining provided superior compositional control. By the early twentieth century, the open-hearth largely displaced the Bessemer process due to better adaptability and steel quality.

Oxygen steelmaking: the LD and kaldo processes

Although Bessemer envisioned oxygen blowing, the cost of pure oxygen and tuyere wear delayed adoption. After the 1920s, industrial oxygen became available, but it was not until the late 1940s that Robert Dürrer pioneered top-blown oxygen steelmaking using a water-cooled supersonic lance (Dutta and Chokshi 2020). The first LD (Linz–Donawitz) converter (1952, Fig. 16) rapidly replaced Bessemer and open-hearth furnaces. It achieved fast decarburization, high productivity, and consistent quality (Failed 1979; Tupkary 1991). For high-phosphorus ores, variants such as LD-AC/ARBED and OLP/IRSID injected oxygen and lime in two stages: first oxidizing C and P (slag removed as fertilizer), then continuing to decarburize (Madías 2011). The Kaldo process (1956, Fig. 17) offered a rotary converter design. Vessel rotation improved mixing and heat transfer, achieving efficient dephosphorization and allowing up to 50% scrap use. However, refractory wear and changing raw material supplies led to its decline by the late 1970s.

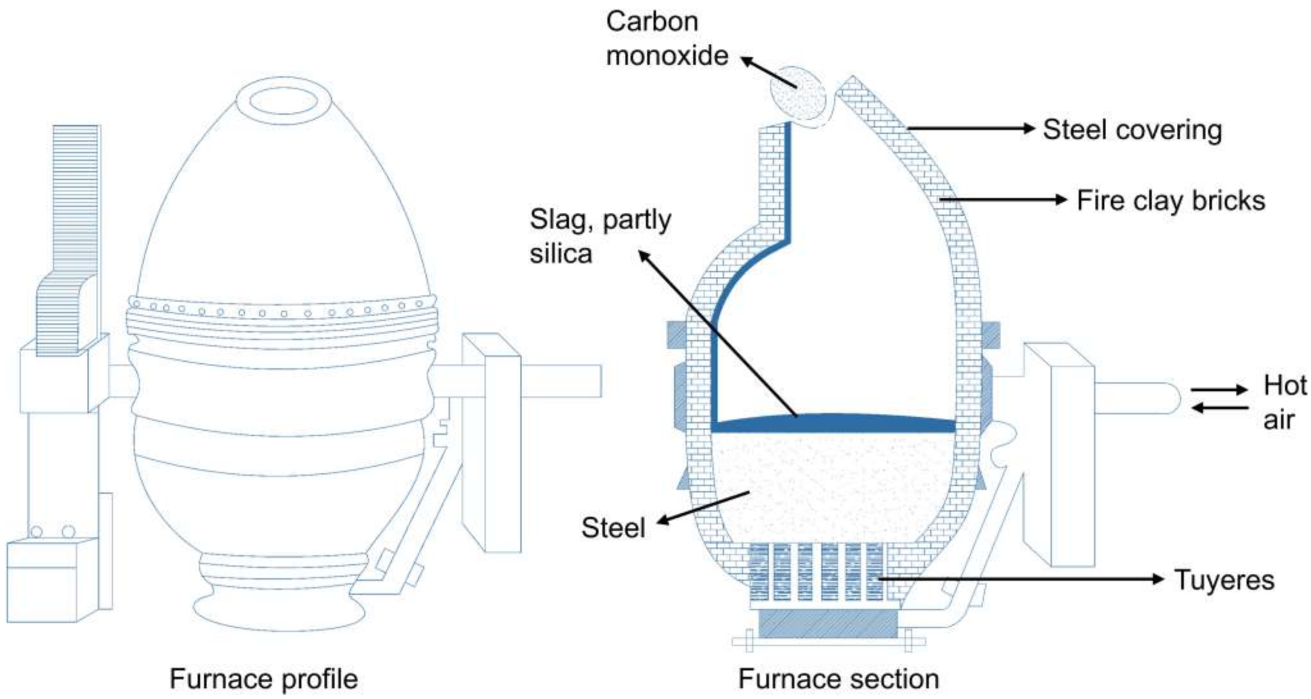

Fig. 14 The Bessemer converter, a pioneering steelmaking vessel of the nineteenth century. Figure (A) shows the external view of the converter, while (B) presents a cross-section illustrating the refractory lining and tuyère arrangement for blowing air through molten pig iron, enabling rapid decarburization and large-scale steel production (Bessemer 1905)

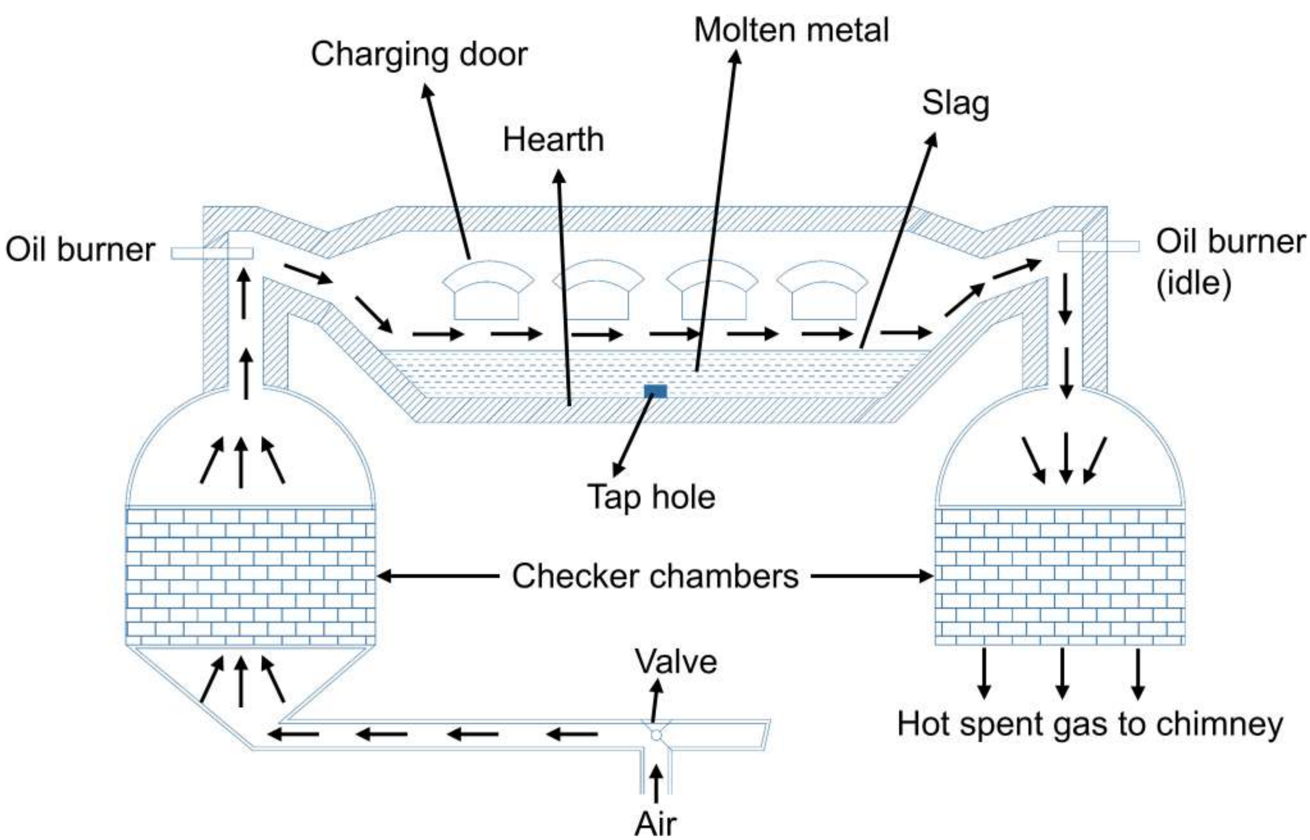

Fig. 15 Diagram of an open-hearth furnace used in steelmaking. The figure illustrates the charging door, hearth, burners, checker chambers, and tap hole. Preheated air and gas pass through checker chambers to sustain combustion, while molten metal and slag accumulate in the hearth, highlighting a process that enabled large-scale steel production before the advent of basic oxygen furnaces (Bessemer 1905)

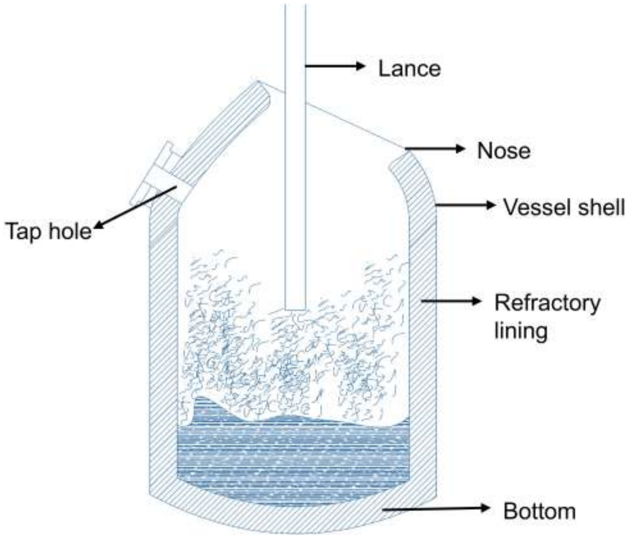

Fig. 16 Cross-sectional diagram of an LD (Linz–Donawitz) converter used in basic oxygen steelmaking. The figure shows the oxygen lance blowing onto the molten bath, refractory-lined vessel shell, tap hole, and bottom design. This converter revolutionized steelmaking by enabling fast decarburization and large-scale production with superior efficiency (Tupkary 1991)

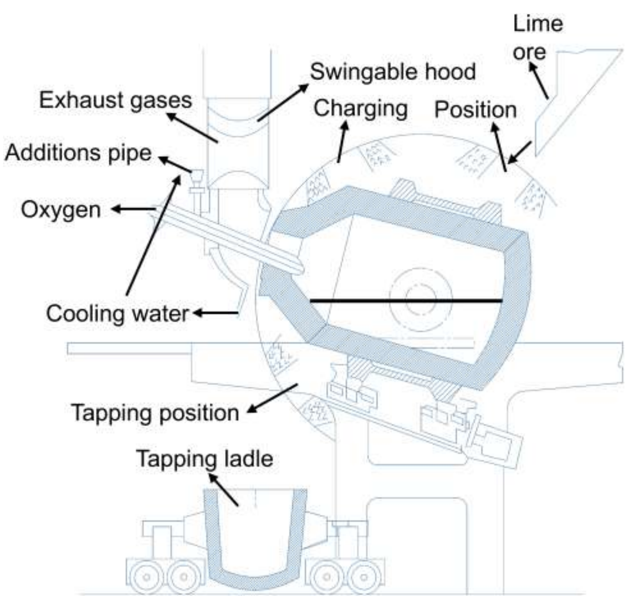

Fig. 17 Cross-sectional diagram of the Kaldo process, a rotary oxygen steelmaking converter. The figure illustrates the charging positions for scrap and hot metal, lime and ore chute, solid additions pipe, oxygen supply, and vessel rotation mechanism. The design allows efficient mixing, refining, and decarburization, with tapping and off-gas removal optimized through controlled rotation (Tupkary 1991)

Combined and bottom-blown converters

Limitations of the LD process—weak bath agitation, slow slag–metal reactions, and risk of over-oxidation—prompted new designs.

- OBM/Q-BOP (1967): bottom-blown converters with tuyeres for oxygen injection, improving stirring.
- Combined blowing (late 1970s, Fig. 18): hybrid systems with top oxygen blowing and bottom inert gas stirring. These enhanced slag–metal reactions, reduced over-oxidation, and improved energy efficiency.

Evolution of copper metallurgical techniques

Copper (Cu) is one of the earliest metals utilized by humankind, with smelting practices dating back to the 5th millennium BCE. Over time, copper extraction advanced from simple crucible smelting to large-scale furnace metallurgy and, in the modern era, to flash and continuous processes that dominate global production (Budd and Taylor 1995; Budd et al. 1992). The evolution of Cu smelting illustrates not only technological innovation but also changing industrial demands, resource availability, and environmental awareness.

Early copper smelting: crucibles to furnaces

The earliest Cu smelting involved crucibles—ceramic vessels used for reducing ores with charcoal. By ~ 5000 BCE, bowl furnaces appeared, serving as transitional reactors between crucible smelting and shaft furnaces (Brodie 1997). While crucibles remained dominant in some regions (e.g., pre-Columbian America), furnace metallurgy eventually supplanted them due to higher productivity.

- At Abu Matar (southern Levant), ore was smelted in bowl furnaces, while crucibles were used for refining and casting (Gale et al. 2000).
- By the 4th millennium BCE, copper smelting at Feynan had scaled to proto-industrial levels, involving ore preparation, smelting, refining, and ingot casting (Gamkrelidze and Ivanov 1983).
- In southeastern Europe, furnace-based metallurgy emerged after the “Balkan Dark Age,” marking a sudden technological leap (Jarrige 1984).

Crucibles, however, retained a role in remelting, alloying, and lost-wax casting, a technique that spread widely in India, the Middle East, and Europe.

Classical pyrometallurgical processes

Over centuries, copper smelting converged into two dominant pyrometallurgical methods:

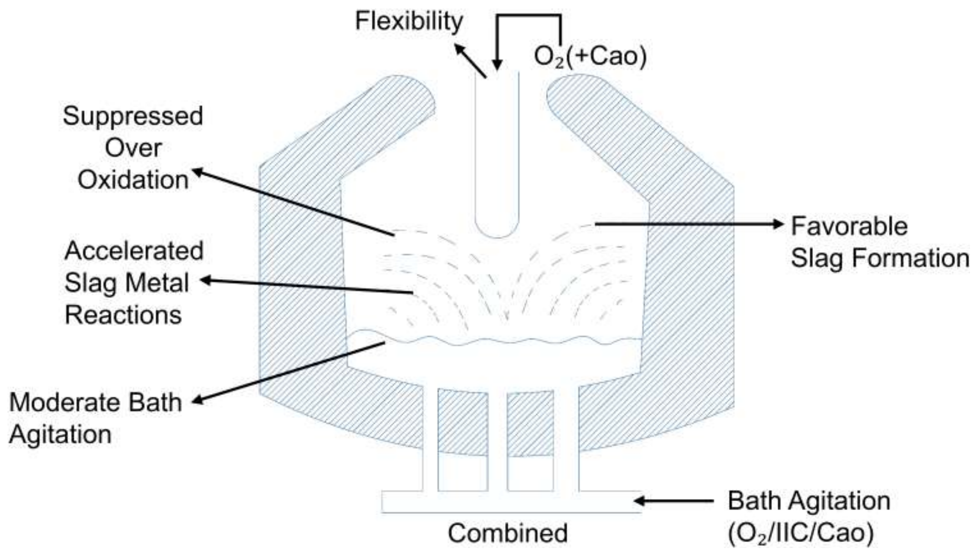

Fig. 18 Diagram of the combined blowing process used in steelmaking. Oxygen (with CaO) is supplied from the top lance, while bottom tuyeres inject gases to enhance bath agitation. The process suppresses over-oxidation, accelerates slag–metal reactions, and promotes favorable slag formation, offering improved flexibility and refining efficiency compared to conventional converters (Tupkary 1991)

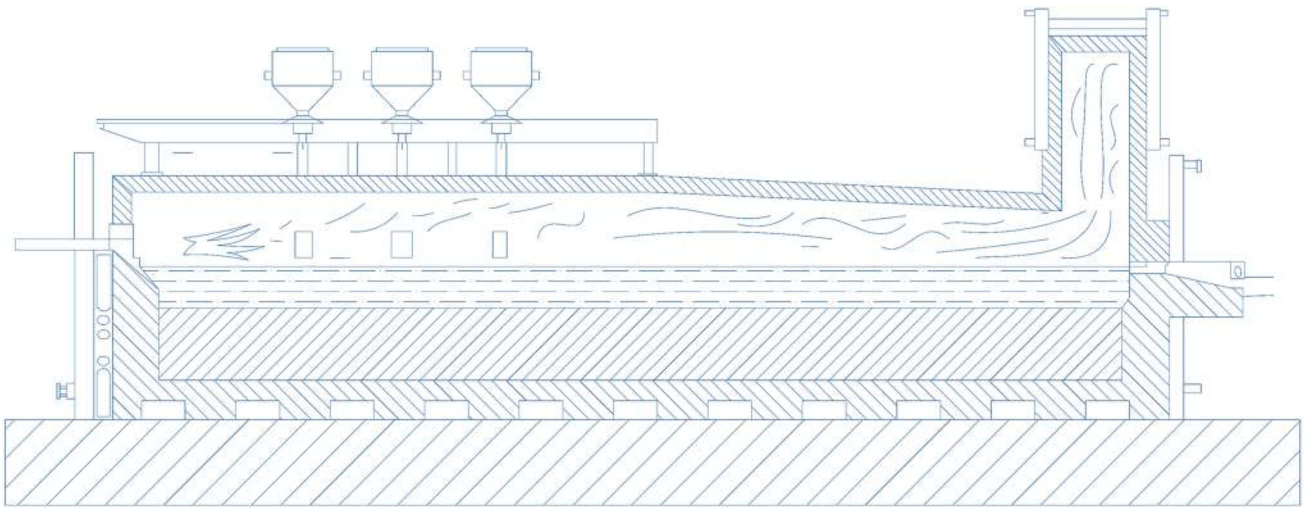

Fig. 19 Cross-sectional diagram of a reverberatory furnace, where heat from burners is reflected off the roof onto the charge. This furnace design enables large-scale smelting and refining by separating the fuel from direct contact with the ore, making it a widely adopted technology in non-ferrous metallurgy (Affinerie et al. 1966)

- Bath smelting – ore/concentrate reacts directly with molten slag and matte; air or oxygen is injected to oxidize impurities.
- Flash smelting – finely ground concentrate is injected into an air/oxygen jet; oxidation and smelting occur while particles remain suspended in the gas stream.

Traditional reverberatory furnaces (Fig. 19) were widely adopted during the 19th–twentieth centuries. Here, burners reflected heat off the arched roof onto the charge, separating slag and matte. Although robust, reverberatories consumed ~ 60% more energy than flash processes and required intensive manual operations (Cocquerel 1995; Affinerie et al. 1966).

Modern flash smelting

The twentieth century marked a revolution in Cu metallurgy through flash smelting, driven by the need for efficiency and emission control. Outokumpu process (Finland, 1940s) – A closed autogenous system where concentrate is injected with oxygen-enriched air; up to 99% SO_2 capture allows sulfuric acid recovery. Produces 45–70% Cu matte (Fig. 20) (Davenport et al. 2002).

- INCO process (Canada, 1950s) – Uses > 96% oxygen in a horizontal reactor; adaptable to various feed chemistries, producing high-grade matte (65–70% Cu) with flexible heat balance (Fig. 21) (Queneau and Marcuson 1996).

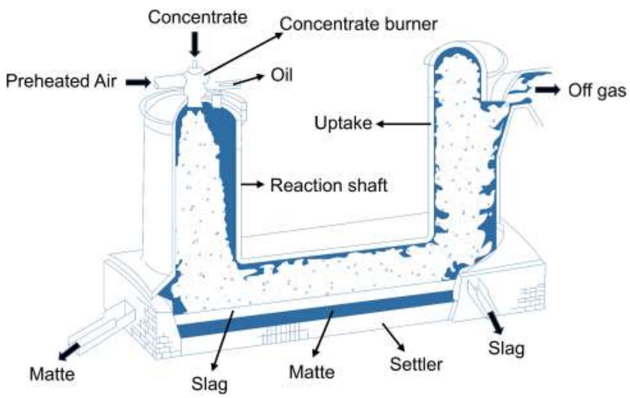

Fig. 20 Diagram of the Outokumpu flash smelting process, where preheated air and concentrate are injected through burners into the reaction shaft. The figure shows matte and slag separation in the settler and the release of off-gas, highlighting the efficiency of this modern pyrometallurgical technique (Davenport et al. 2002)

- KIVCET process (USSR, 1970s) – Designed for complex concentrates containing Pb and Zn; uses a cyclone smelter with partitioned reduction settling, achieving efficient matte/slag separation (Fig. 22) (Moskalyk and Alfantazi 2003).
- CONTOP process (Germany, 1979) – Combines cyclone flash smelting with top-blowing; achieves high-grade matte (~80% Cu) and generates high-SO_2 off-gas (up to 26%) for acid recovery (Fig. 23) (Brueggemann and Caba 1998).

Continuous smelting and converting

The shift from batch to continuous copper metallurgy was pioneered in the late twentieth century.

- Mitsubishi Process (Japan, 1974) – Fully continuous, using three interconnected furnaces for matte smelting, slag cleaning, and converting. Produces blister copper (~99% Cu) with efficient gravity flow of molten streams (Fig. 24) (Shibasaki et al. 1993).
- Isasmelt Process (Australia, 1980s) – Employs a top-entry Sirosmelt lance for intense bath agitation; operates autogenously with oxygen-enriched air. Widely adopted due to compact design, high SO_2 recovery, and low fuel demand (Fig. 25) (Rentz et al. 1999). India's Tuticorin smelter (Sterlite Industries) hosts one of the world's largest Isasmelt units, processing ~600,000 tpa concentrate (Mounsey and Robilliard 1994; Ullmann et al. 1995).
- Noranda Process (Canada, 1970s) – Horizontal steel-barrel reactor, continuous concentrate injection with oxygen-enriched air; produces 70–75% Cu matte while capturing SO_2-rich off-gas for acid plants (Fig. 26) (Bailey and Storey 1979; Mills et al. 1976; Prevost 1992).
- Teniente (CMT) Process (Chile, 1970s) – Converter-based method using molten matte as fuel; produces 72–77% Cu matte. Widely applied in Latin America, with environmental upgrades for higher oxygen enrichment (Fig. 27) (Campos et al. 1991).

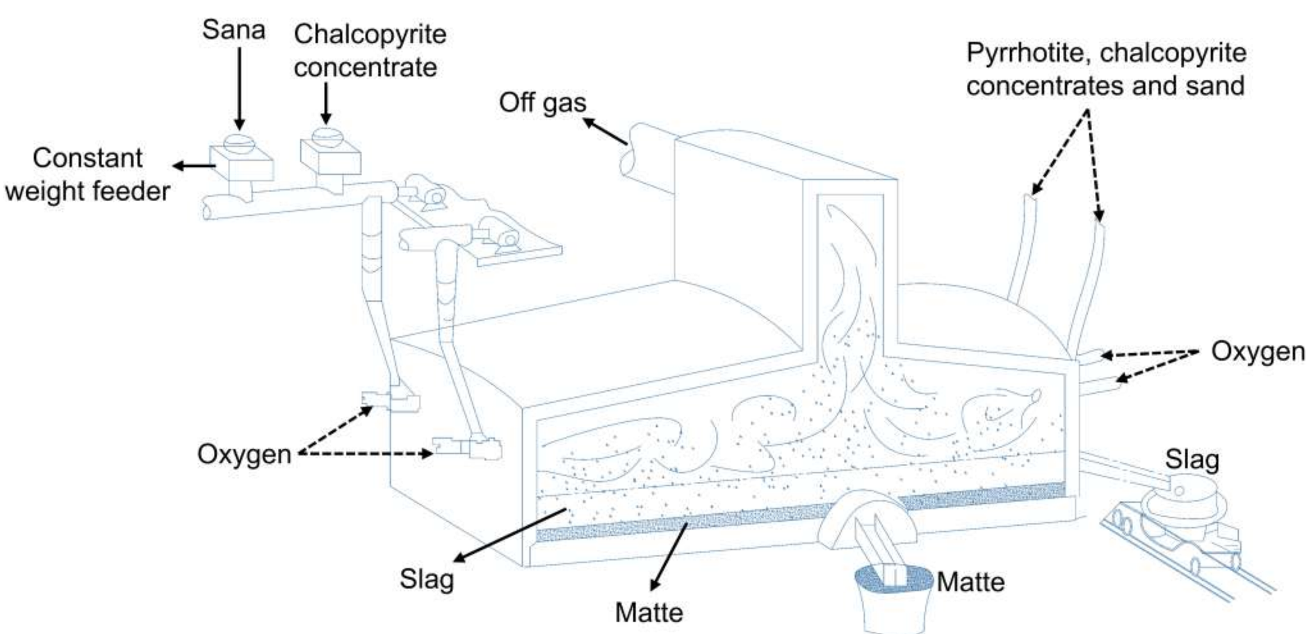

Fig. 21 Diagram of the INCO flash smelting process, in which pyrrhotite and chalcopyrite concentrates are injected with oxygen into the reaction shaft. The figure illustrates the continuous separation of matte and slag, along with the release of off-gas, representing a major advancement in copper smelting technology (Queneau and Marcuson 1996)

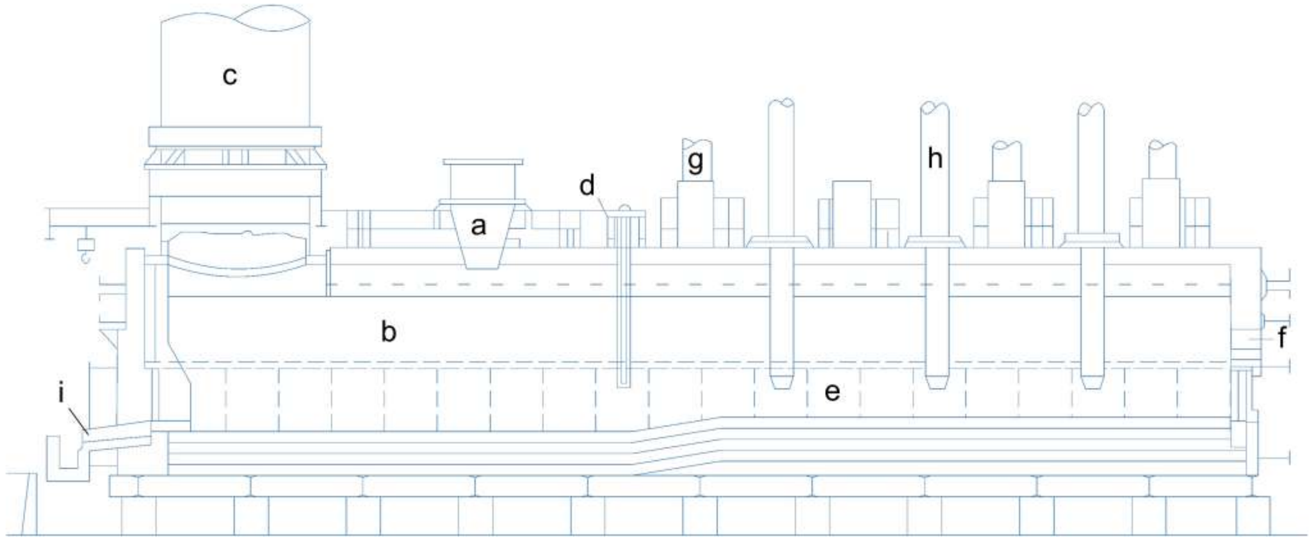

Fig. 22 Cross-sectional schematic of the KIVCET furnace used for continuous smelting. The main components include: (a) smelting cyclone, (b) separating chamber, (c) cyclone waste-gas offtake, (d) partition wall, (e) settling reduction hearth, (f) slag tap hole, (g) reductant feed and waste-gas offtake from the hearth, (h) electrical resistance heating, and (i) matte tap hole. This design integrates cyclone smelting with reduction settling to achieve efficient matte and slag separation (Moskalyk and Alfantazi 2003)

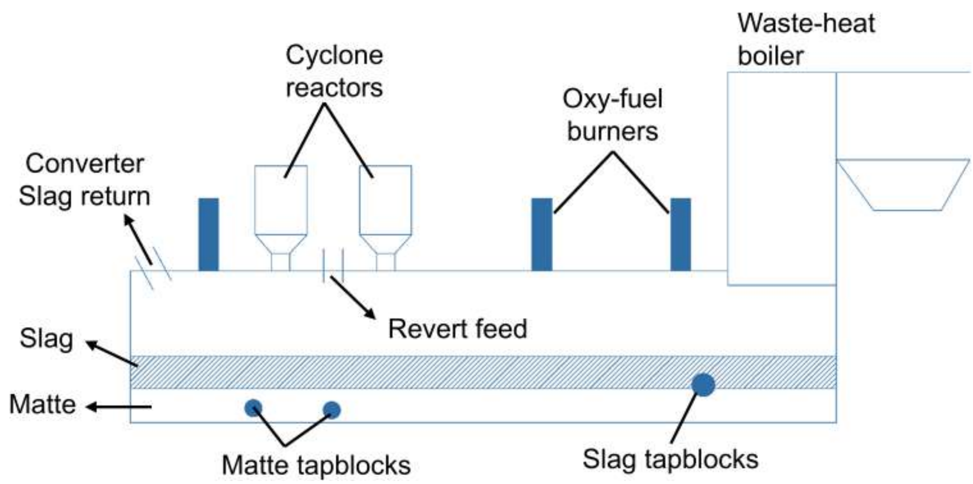

Fig. 23 Diagram of the Contop furnace, illustrating its main components and process flow. The design integrates cyclone reactors, oxy-fuel burners, and a waste-heat boiler, with distinct slag and matte layers tapped through designated outlets. Converter slag return and revert feed enhance process efficiency, making the Contop furnace an important advancement in continuous smelting technology (Brueggemann and Caba 1998)

From electrorefining to sustainability

The Industrial Revolution expanded copper use in electrical applications, driving the adoption of electrolytic refining in the late nineteenth century. Electrorefining enabled > 99.9% purity cathodes, critical for conductivity.

Today, flash and continuous smelting processes dominate due to:

- High throughput (hundreds of thousands of tonnes per year),
- Efficient energy use,
- Integration with acid plants for SO_2 capture,
- Lower labor intensity and higher automation.

Environmental sustainability now shapes copper metallurgy: off-gas cleaning, sulfur capture, slag recycling, and energy-efficient designs (e.g., oxygen-enriched lances, waste-heat recovery) reduce the ecological footprint. In India, modern smelters like Tuticorin (Isasmelt) and Khetri (HCL) integrate these global innovations with local resource supply, ensuring competitiveness and compliance with environmental standards.

Modern techniques in copper

Copper ores, mining, and beneficiation Copper occurs as native metal and in oxides (e.g., cuprite, malachite, azurite, chrysocolla) and sulfides (e.g., chalcopyrite, bornite, chalcocite, covellite). Orebodies are mined by open-pit (lower grade, large tonnage) or underground (higher grade) meth-

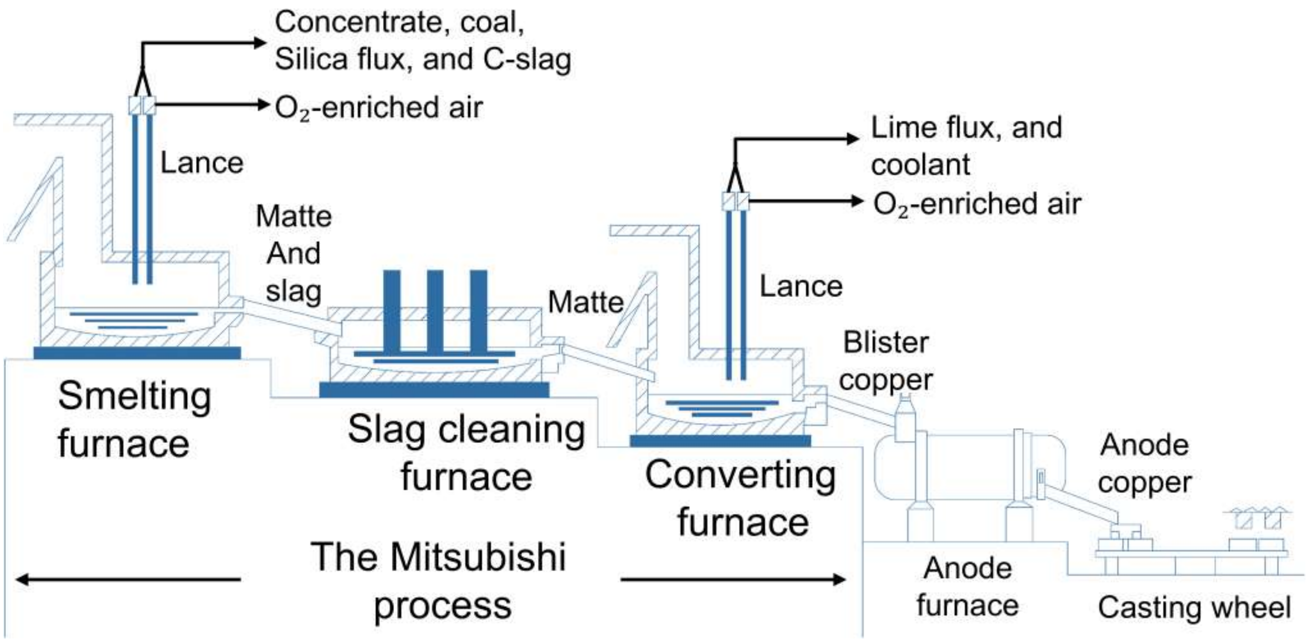

Fig. 24 Flow diagram of the Mitsubishi continuous copper smelting process. The figure illustrates the smelting furnace, slag-cleaning furnace, and converting furnace, where oxygen-enriched air and fluxes are injected for efficient matte-to-blister copper conversion. The process is fully continuous, leading to anode copper production and casting, representing a major advancement in pyrometallurgical technology (Shibasaki et al. 1993)

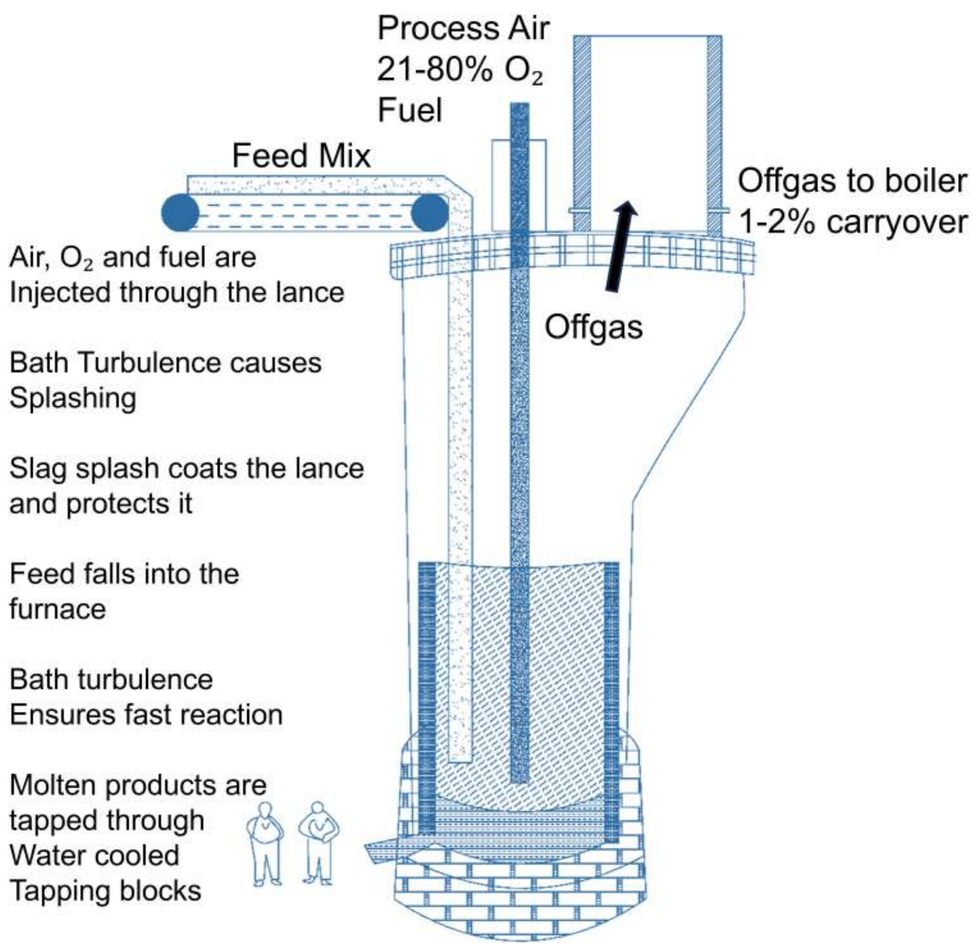

Fig. 25 Diagram of the Isasmelt furnace system. Pelletized concentrates, fluxes, coal, and fine reverts are injected through a vertical lance along with natural gas and oxygen-enriched air. The design promotes intense bath agitation, efficient smelting, and the release of off-gas through the furnace uptake, representing a compact and energy-efficient smelting technology (Mounsey and Robilliard 1994)

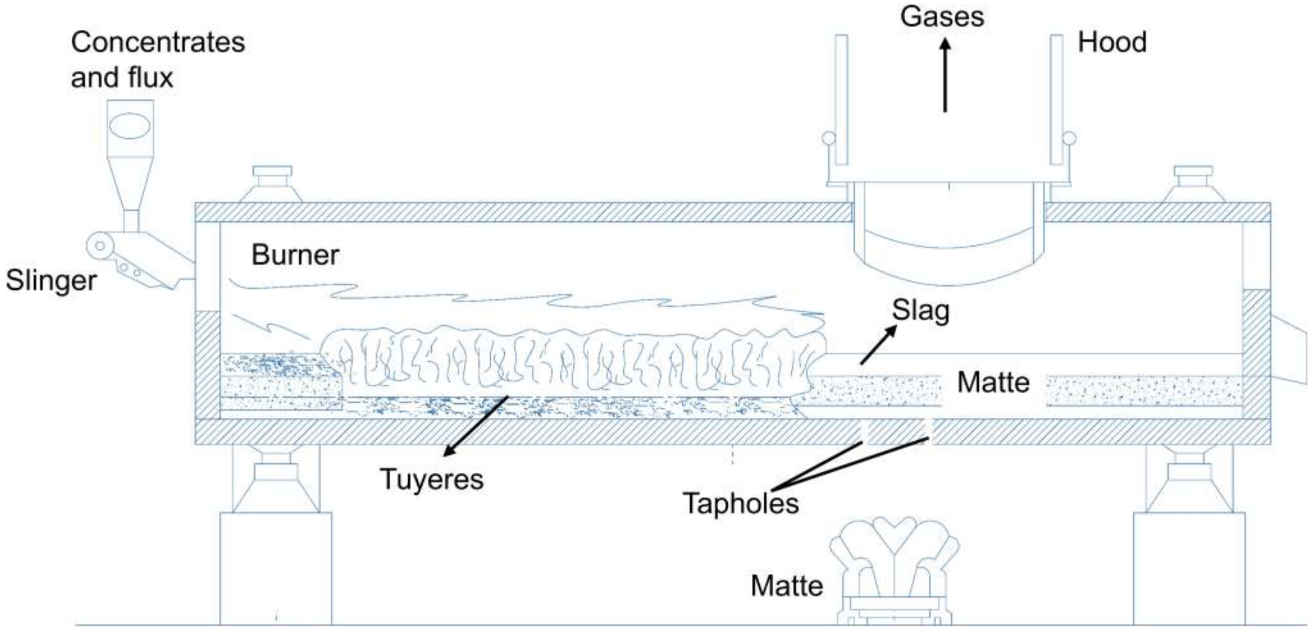

Fig. 26 Diagram of the Noranda smelting process. Concentrates and flux are introduced through a slinger, while oxygen-enriched air is injected via tuyeres to sustain combustion. The furnace design facilitates the separation of slag and matte, with gases exiting through a hood and products tapped through dedicated outlets, representing an important innovation in continuous copper smelting (Prevost 1992)

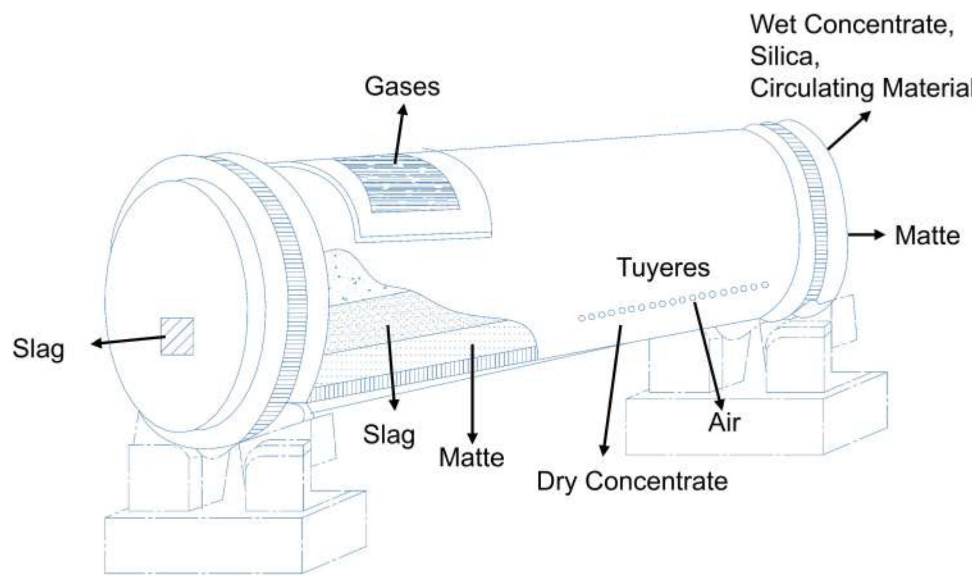

Fig. 27 Diagram of the Teniente smelting process. Bone-dry concentrate, wet feed, reverts, and silica are injected through tuyeres with air and oxygen to sustain the reaction. The furnace design enables efficient conversion of matte into white metal, with slag and off-gases removed through separate outlets, making it a widely adopted technology in copper metallurgy (Campos et al. 1991)

ods, then crushed and ground. Gangue (quartz, carbonates, silicates) is separated by flotation (for most sulfides) or leach-based routes (for many oxides and some secondary sulfides) (Failed 2001a). At plant scale, copper extraction follows two families of routes:

- Conventional pyrometallurgy (concentrate → smelting/converting → blister → electrorefining), and
- Hydrometallurgy via solvent extraction–electrowinning (SX–EW) (leach solution → SX → EW cathode).

SX–EW hydrometallurgy (low-grade oxides/secondary sulfides) SX–EW became widespread from the 1970s (Arizona, Chile, Africa) and matured in the 1980s with better extractants and plant design (Arbiter and Fletcher 1994). Leaching. Acidic solutions dissolve copper from oxide ores, low-grade dumps/heaps, tailings, and some secondary sulfides. Emerging bio- and in-situ leaching lower mining/milling footprints by solubilizing copper in place and reducing haulage/waste handling (Failed 2001b). The pregnant leach solution (PLS)—Cu^{2+} in sulfate—feeds SX.

Solvent extraction (SX). An organic extractant selectively transfers Cu from PLS to the organic phase; stripping regenerates the organic and produces a purified, high-Cu electrolyte.

Electrowinning (EW). Cu^{2+} is plated at the cathode, yielding LME-grade cathode comparable to electrorefined copper. Why SX–EW? Lower capex/opex at small–medium scales, modularity, high energy efficiency, tight SO_2 control (no smelter stack), and compelling environmental performance make SX–EW a dominant route for many oxide resources (Moats and Free 2007).

Bioleaching: principles, mechanisms, and industrial practice Bioleaching uses acidophilic Fe/S-oxidizing bacteria/archaea to generate ferric sulfate and sulfuric acid, which oxidize sulfide minerals and keep Fe cycling ($Fe^{2+} \leftrightarrow Fe^{3+}$) (Liu et al. 2023; Ma et al. 2021). The process is exothermic and proceeds at mineral–solution interfaces where biofilms enhance kinetics (Fig. 28) (Bhatti et al. xxxx).

Bacterial oxidation of pyrite, ferrous iron, and elemental sulfur:

$FeS_2 + 3½O_2 + H_2O \rightarrow FeSO_4 + H_2SO_4$ (Bacterial process).

$2FeSO_4 + H_2SO_4 + 0.5\ O_2 \rightarrow Fe_2\ (SO_4)_3 + H_2O$ (Bacterial process).

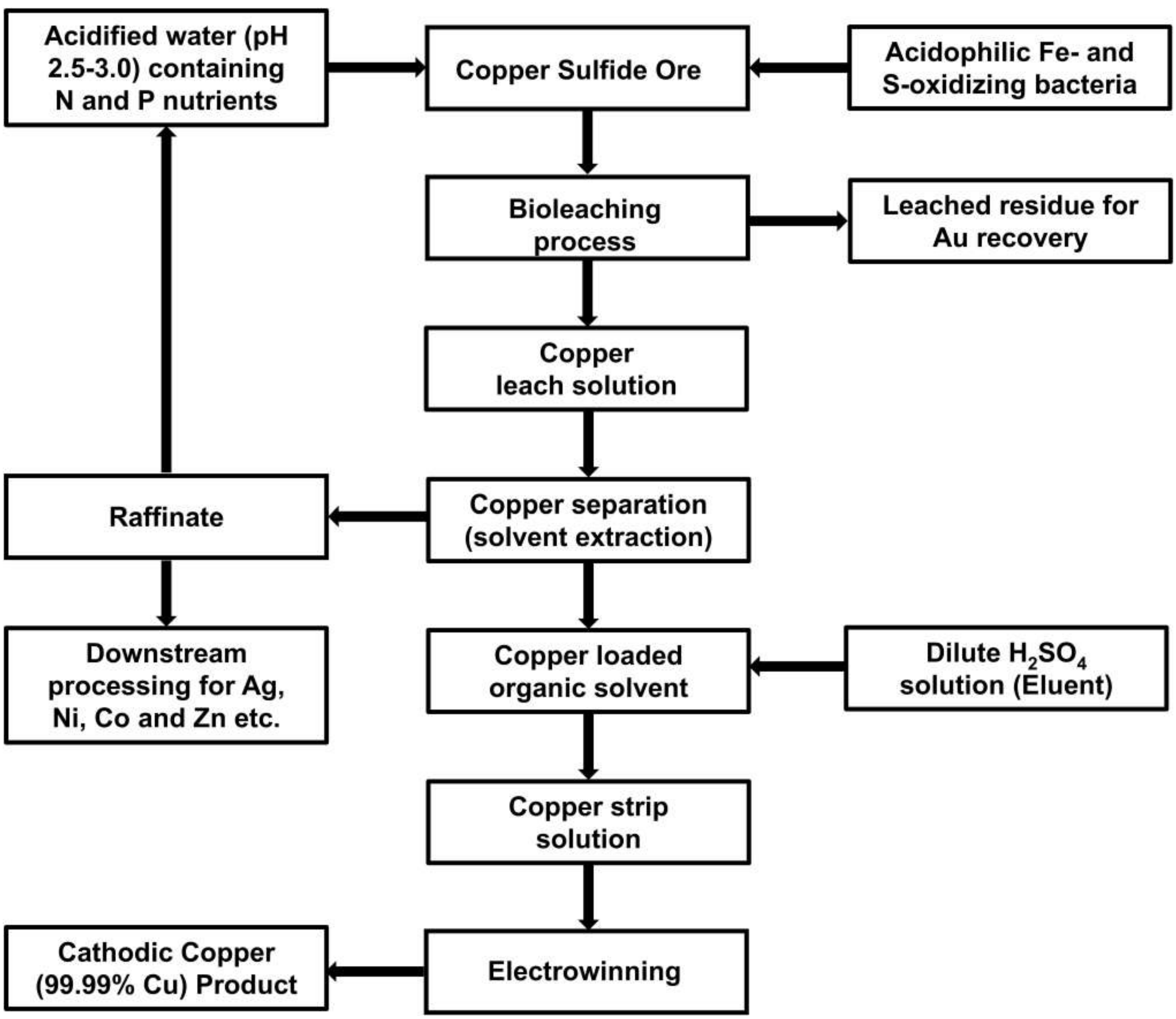

Fig. 28 Flow sheet depicting the bioleaching process for copper sulfide ores. Acidophilic Fe- and S-oxidizing bacteria facilitate bioleaching, producing a copper-rich leach solution. Subsequent solvent extraction and electrowinning yield cathodic copper (99.99% Cu), with raffinate recycled and downstream recovery possible for Ag, Ni, Co, and Zn. This process highlights an eco-friendly alternative to conventional pyrometallurgical routes (Bhatti et al. xxxx)

$Fe_2(SO_4)_3 + FeS_2 \rightarrow 3FeSO_4 + 2S^0$ (Chemical process).

$2S^0 + 3O_2 + 2H_2O \rightarrow 2H_2SO_4$ (Bacterial process).

Cu dissolution from ores containing primary and secondary sulfide minerals:

Bacterial oxidation of chalcocite.

$CuS + 3½O_2 + H_2O \rightarrow CuSO_4 + H_2SO_4$.

Bacterial oxidation of covellite.

$Cu_2S + 3½O_2 + H_2O \rightarrow 2CuSO_4 + H_2SO_4$.

Bacterial oxidation of chalcopyrite.

$CuFeS_2 + O_2 + 2H_2SO_4 \rightarrow CuSO_4 + FeSO_4 + 2S^0 + 2H_2O$.

$CuFeS_2 + 4Fe^{3+} \rightarrow Cu^{2+} + 5Fe^{2+} + 2S.^0$

$CuFeS_2 + 4Fe^{3+} + 3O_2 + H_2O \rightarrow Cu^{2+} + 5Fe^{2+} + 2H_2SO_4$.

Cu is extracted from ores through direct and indirect bioleaching mechanisms. In direct bioleaching, microorganisms interact directly with oxidation-prone minerals, enabling an enzymatic reaction that separates metal from the ore. In contrast, indirect bioleaching does not involve direct contact between microorganisms and minerals; microbes produce leaching agents, such as sulfuric acid and ferric sulfate, which oxidize the ore externally. Figure 29 illustrates the direct (contact, single-step) and indirect (non-contact, two-step) mechanisms involved in bioleaching Cu from sulfide minerals (Jung et al. 2022).

Industrial implementations: heap, dump, in-situ, stope, and stirred-tank reactors are used depending on ore type and kinetics (Saldaña et al. 2023; Koizhanova et al. 2022). Bioheap leaching stacks agglomerated ore on lined pads; acidified, nutrient-dosed solutions percolate, PLS is collected, and SX–EW completes Cu recovery (Fig. 30).

Why it matters (tech & ESG): low capex/opex, ambient T/P, in-situ H_2SO_4/Fe^{3+} generation, no SO_2 stacks, and straightforward neutralization. Challenges include slow kinetics for chalcopyrite, temperature control, and solution management—addressed via thermophiles, improved aeration, and agglomeration chemistry.

Flotation of Cu minerals (sulfides and oxides) Flotation is the workhorse for upgrading Cu sulfide ores; adapted variants enable oxide beneficiation (Zhang et al. 2022). Ground pulp is conditioned with collectors (e.g., xanthates, dithiophosphates), frothers, activators, depressants, and pH modifiers to tune surface hydrophobicity (Park et al. 2020, 2021; Aikawa et al. 2021; Bulatovic 2007). Injected air creates bubbles; hydrophobic particles attach and report to froth concentrate, while gangue remains as tailings (Yuan et al. 1996; Sripriya et al. 2003).

- Direct flotation: collectors/frothers added without prior activation (Han et al. 2021).
- Sulfidization flotation (for oxides): sodium sulfide/NaHS forms a thin Cu–sulfide layer on oxides, enabling capture by sulfide collectors—overcoming poor selectivity of direct collectors (Fig. 31)(Bilal et al. 2022).

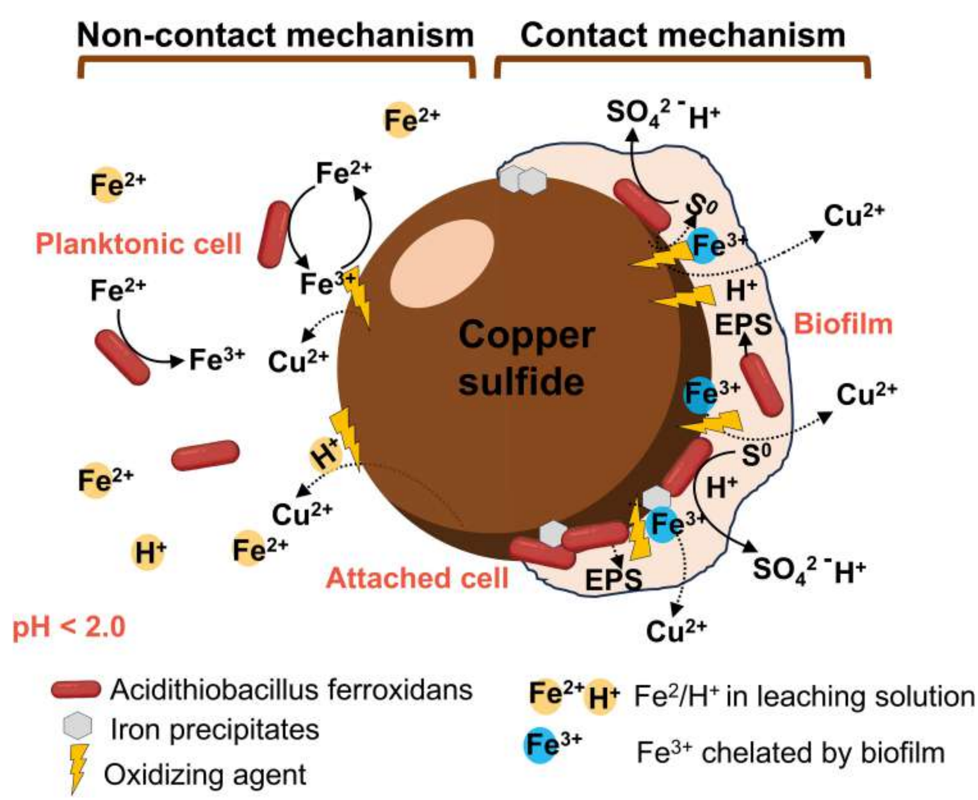

Fig. 29 Schematic diagram illustrating the bioleaching of copper from sulfide minerals. The contact (direct, single-step) mechanism involves microbial attachment to the mineral surface and localized oxidation, while the non-contact (indirect, two-step) mechanism relies on ferric ions generated by planktonic cells in solution. Together, these pathways explain the role of Acidithiobacillus ferrooxidans and associated reactions in the microbial dissolution of copper sulfides under acidic conditions (Jung et al. 2022)

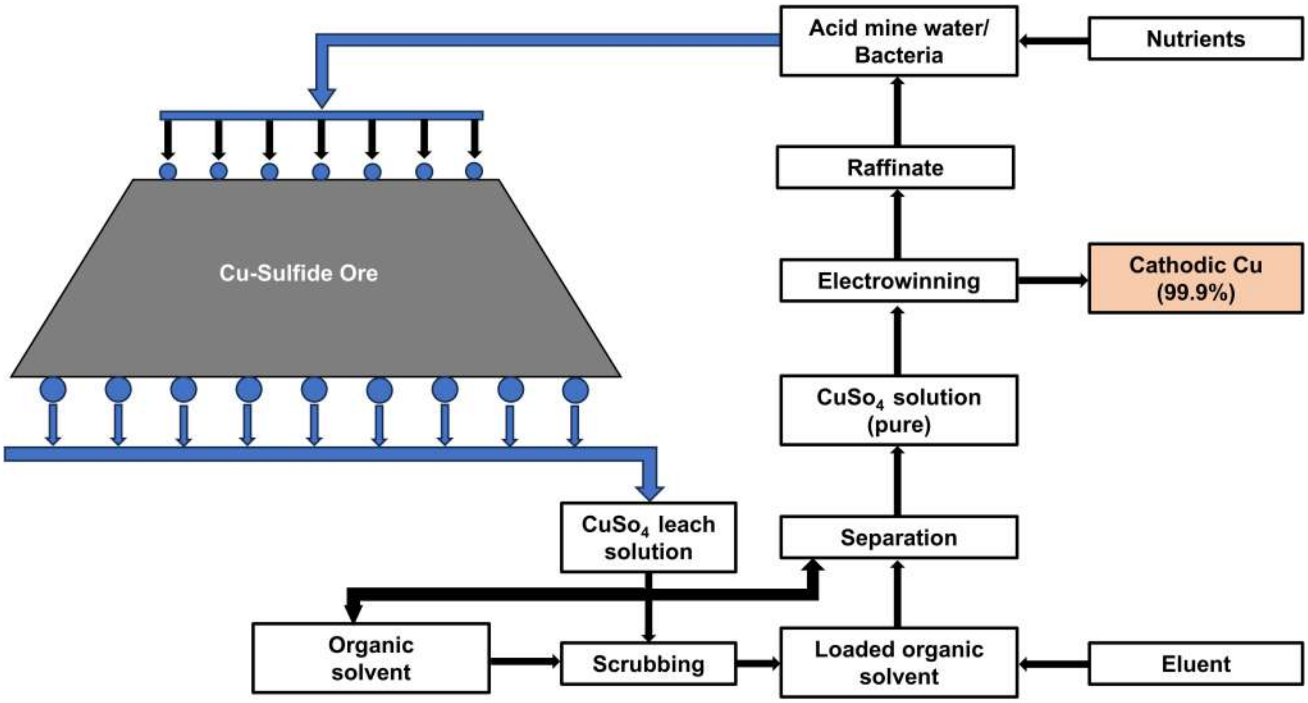

Fig. 30 Schematic illustration of the bioheap leaching process for copper sulfide ore. Acid mine water enriched with bacteria and nutrients percolates through the ore heap, generating a $CuSO_4$-rich leach solution. The solution undergoes solvent extraction, scrubbing, and separation, followed by electrowinning to produce high-purity cathodic copper (99.9%). Raffinate is recycled for continued bioleaching, making this an efficient and environmentally sustainable copper recovery route (Bhatti et al. xxxx)

Modern bronze processing and alloy design

Melting & casting. Induction and electric arc furnaces provide clean, controllable melting; continuous casting yields bars/rod/strip with tight chemistry and microstructure. For complex shapes (art, aerospace, precision hardware), investment casting (lost-wax) remains standard; CAD/CAM and 3D-printed patterns/molds accelerate prototyping and improve fidelity. Alloy families and applications:

- Phosphor bronze (Cu–Sn–P): high elasticity, low friction → springs, musical strings, connectors.
- Nickel–aluminium bronze (NAB): exceptional corrosion/erosion resistance → marine propellers, pumps, valves.
- Manganese bronze (high-strength brasses): high strength, good seawater resistance → heavy-duty marine/industrial hardware.
- Silicon bronze (Cu–Si): good conductivity, oxidation resistance → electrical and plumbing components.

Surface engineering & sustainability. Patination (chemical/thermal) provides protective/aesthetic films for art and architecture. Rising recycling rates, alloy-sorting sensors, and low-loss remelting cut energy and CO_2 while preserving alloy integrity—reducing primary Cu/Sn demand and supporting circularity. India applies both families of technologies: pyrometallurgy at integrated smelters/refineries (e.g., Tuticorin's Isasmelt route; Khetri for Cu) and hydrometallurgy for specific oxide/low-grade resources. Downstream bronze foundries routinely use induction melting, investment casting, and continuous casting for industrial and heritage applications.

Developments in Zinc (Zn) processing

From early distillation to industrial metallurgy

Early zinc production was pioneered in India (Rajasthan) via downward distillation in ceramic retorts (late 1st–early 2nd millennium CE), and later in China (14th c.). Ores (commonly sphalerite, ZnS) were heated so that zinc vapor condensed in a cooler zone—an elegant solution to zinc's low boiling point (907 °C) and re-oxidation tendency. Europe adopted retort smelting from the 16th–nineteenth centuries (horizontal → vertical/Silesian variants), which enabled larger throughputs but remained labor-intensive.

Electrolytic zinc and the rise of hydrometallurgy

By the late 19th–early twentieth century, electrolytic refining unlocked high-purity Zn from lower-grade feeds: ore

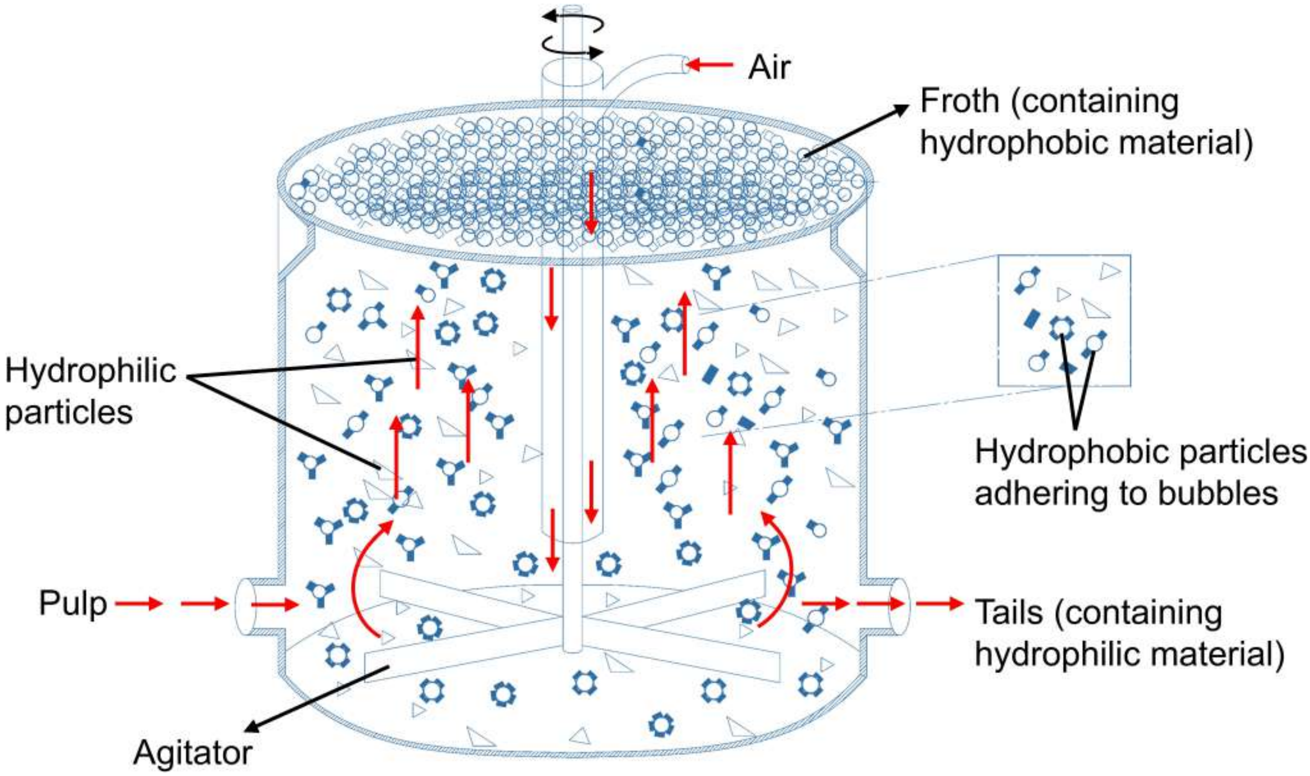

Fig. 31 Diagram of a flotation cell used in mineral processing. Air bubbles introduced at the base attach to hydrophobic particles in the pulp, which rise to the surface to form a froth layer, while hydrophilic particles remain in suspension. This selective separation process is fundamental to the concentration of copper and other sulfide ores (Bilal et al. 2022)

was converted to a sulfate electrolyte ($ZnSO_4$) and electrowon at the cathode, dramatically improving purity and yield. The mid-twentieth century introduced two industrial workhorses:

- Imperial Smelting Process (ISP)—a blast-furnace route that co-smelts lead–zinc concentrates. Versatile for mixed feeds, but energy-intensive; less common today.
- Roast–Leach–Electrowin (RLE)—now the dominant flowsheet. Roasting converts $ZnS \rightarrow ZnO + SO_2$ (captured for acid); leaching forms $ZnSO_4$ solution; purification removes Fe, Cu, Co, Ni; EW yields LME-grade cathodes.

Key impurity management advances include jarosite and goethite processes to fix iron (Fe) as stable residues, reducing environmental risk and improving electrolyte quality.

Newer leaching routes, bio-options, and recycling

To avoid roasting and tackle refractory feeds:

- Direct atmospheric leaching (catalyzed ferric systems) and pressure leaching (elevated T/P) dissolve ZnS more completely, cutting SO_2 emissions and improving kinetics.
- Bio-hydrometallurgy leverages sulfur- and iron-oxidizing microbes to generate ferric sulfate/acid in situ, enabling low-energy treatment of marginal ores and residues.
- Recycling of galvanizing ash/dross, EAF dusts, batteries, and brass/bronze scrap uses pyro (Waelz, fuming) and hydro (leach–purify–EW) routes, anchoring Zn in the circular economy.

Why these shifts endured. Hydrometallurgical routes (RLE, pressure/direct leach, SX/EW variants) scaled because they deliver high purity, SO_2 control via acid plants or no SO_2 at all, robust Fe removal, and lower energy per tonne—with clear pathways to treat complex feeds and recover co-metals (e.g., Ag, In, Ge).

Developments in gold (Au) processing

From gravity and fire assay to amalgamation

Gold's early metallurgy exploited its native occurrence: panning, sluicing, and gravity concentration separated dense Au from alluvials. Fire assay (ancient Egypt) quantified purity. From the medieval period onward, amalgamation with mercury extracted fine gold from crushed ore—effective but toxic and environmentally damaging.

Why these shifts endured. Cyanidation persists for its high selectivity and recovery on broad ore types; POX/BIOX enable refractory ores; gravity/flotation reduce reagent footprints; and detox/water stewardship align the circuit with modern ESG expectations.

Cyanide era and core circuit chemistry

The pivotal advance was cyanidation (MacArthur–Forrest): finely ground ore contacts alkaline cyanide; dissolved Au forms $[Au(CN)_2]^-$, then is recovered by zinc precipitation (Merrill–Crowe) or adsorption on activated carbon:

- CIP/CIL (1970s): Carbon-in-Pulp/Carbon-in-Leach load gold directly from slurry, simplifying circuits and improving recovery, especially where preg-robbing carbonaceous matter exists (CIL advantage).
- Electrowinning/Elution: Loaded carbon is stripped; Au is electrowon and refined to bullion.
- Heap leaching extended cyanidation to low-grade ores: crushed ore on lined pads is irrigated with dilute cyanide; pregnant solution is processed by CIC/CIL or Merrill–Crowe.

Unlocking refractory ores: oxidation pretreatments

When Au is locked in sulfides or arsenides (e.g., pyrite, arsenopyrite), pretreatment is needed to expose gold to cyanide:

- Pressure oxidation (POX): autoclave oxidation at elevated T/P; rapid, clean off-gas handling.
- BIOX® / bio-oxidation: microbial oxidation of sulfides at moderate T; energy-lean and effective.
- Roasting: thermal oxidation; effective but requires stringent emission control (SO_2/As management).

Alternatives, optimization, and ESG

- Alternative lixiviants: thiosulfate (especially for Cu-bearing ores/carbonaceous matter), glycine, and halide systems target lower-toxicity or niche ores; most are not yet broadly replacing cyanide but are advancing commercially.
- Upstream reduction of cyanide demand: gravity concentration and flotation recover coarse/free gold before leach, shrinking cyanide circuits and reagent use.
- Copper–gold interactions: SART (sulfidization–acidification–recycle–thickening) strips Cu from cyanide solutions, reduces cyanide consumption, and regenerates cyanide improving economics in Cu-rich ores.
- Detox and water: INCO (SO_2/air) cyanide destruction, peroxide/Caros acid, and strict WAD cyanide limits protect receiving waters; closed-loop water and lined, monitored tailings are now standard.

Why these shifts endured. Cyanidation persists for its high selectivity and recovery on broad ore types; POX/BIOX enable refractory ores; gravity/flotation reduce reagent footprints; and detox/water stewardship align the circuit with modern ESG expectations.

Final remarks

Preservation and conservation challenges

The preservation of ancient metallurgical artifacts requires an interdisciplinary approach that combines history, chemistry, materials science, and conservation engineering. Objects made from iron, bronze, copper, silver, and gold often degrade through corrosion, oxidation, or structural cracking. Conservation strategies therefore aim not only to stabilize these objects but also to retain their historical authenticity.

Traditional methods of preservation relied on controlling environmental exposure regulating humidity, temperature, and pollutants—to reduce corrosion. Simple coatings, such as waxes, oils, or lacquers, created protective barriers, while inhibitors such as benzotriazole (BTA) were used to protect copper alloys (MacLeod 2016; Abdel-Karim and El-Shamy 2022). Recent research has developed more effective acidic inhibitors, such as isopropyl benzylidene thiazole, with inhibition efficiencies above 95% (Cano and Lafuente 2013; Antonija 2011).

Modern conservation techniques emphasize diagnostic precision and minimally invasive intervention. Nondestructive tools such as X-ray fluorescence (XRF) and scanning electron microscopy (SEM) allow detailed characterization of corrosion layers and microstructure. Advanced techniques such as laser ablation selectively remove corrosion without damaging the underlying metal, while plasma reduction can convert corrosion products back to metallic phases. Nanotechnology-based coatings, including sol–gel silica or titania films, are increasingly used to create invisible, long-lasting barriers that resist fluctuating humidity and pollutants.

Together, these advances represent a shift from symptomatic treatment to predictive, science-based conservation, ensuring that artifacts like the Delhi Iron Pillar, Chola bronzes, and ancient coins remain accessible for future generations of study and cultural appreciation.

Environmental and socio-economic impacts

Modern metallurgical industries, while essential to economic growth, face major environmental and socio-economic challenges. Iron and steel alone contribute 7–9% of global CO_2 emissions, with additional impacts from sulfur dioxide, nitrogen oxides, and particulate matter. Mining and smelting also disrupt ecosystems through land degradation, deforestation, and water contamination via acid mine drainage and heavy metals. Tailings dams remain a persistent environmental hazard.

Socio-economically, the sector provides employment and infrastructure but often displaces communities, strains water resources, and exposes workers to occupational hazards. Local populations near mining or smelting sites frequently bear disproportionate health burdens, including respiratory illnesses and heavy metal exposure. Economic dependence on metallurgy also leaves regions vulnerable to commodity price fluctuations.

In response, industries are moving towards low-carbon technologies such as hydrogen-based steelmaking, electric arc furnaces, and solvent-extraction electrowinning in copper production. Circular economy approaches scrap recycling, slag valorization, and tailings reprocessing are increasingly prioritized. International initiatives such as the International Council on Mining and Metals (ICMM) and Responsible Steel framework promote higher environmental, social, and governance (ESG) standards.

Thus, while metallurgy continues to underpin industrial economies, its future sustainability depends on reducing emissions, managing wastes responsibly, and balancing economic benefits with community welfare.

Continuities between ancient and modern practices

A striking feature of Indian metallurgy is the continuity between its ancient innovations and modern practices. Several parallels illustrate how traditional insights continue to shape current research and industry:

- Corrosion resistance: The Delhi Iron Pillar (c. 400 CE), with its high-phosphorus, slag-rich microstructure, remains a benchmark for corrosion-resistant design. Modern research into stainless steels and weathering steels echoes these ancient strategies of alloy tuning.
- High-quality steels: Wootz steel, famous for its unique microstructural patterns, inspired later research into high-carbon steels and advanced heat-treatment techniques. Current studies on nano-carbides in ultrahigh carbon steels directly build on these historical precedents.
- Zinc metallurgy: The retort-based downward distillation furnaces at Zawar (Rajasthan) were the earliest known large-scale production of metallic zinc, a technique predating Europe by centuries. Today, zinc hydrometallurgy and recycling methods continue to reflect the Indian tradition of efficiency and innovation.
- Gold and coinage: The Hutti mines and ancient coinage systems highlight India's deep association with gold, which continues in modern refining and electro-winning practices. Cultural continuity ensures gold remains both an industrial and socio-economic pillar.
- Sustainability ethos: Ancient metallurgists practiced recycling (e.g., remelting bronze, reclaiming slag iron) out of necessity. This mindset resonates with modern circular economy approaches, where scrap recovery and resource efficiency are central.

In essence, ancient Indian metallurgy did not merely vanish it provided principles of alloy design, sustainable resource use, and cultural integration that continue to inform modern industrial practices.

Conclusions

The comparative study of ancient and modern Indian metallurgical practices highlights a remarkable continuum of innovation, resilience, and adaptability. Ancient achievements—such as the corrosion-resistant Delhi Iron Pillar, the advanced crucible technologies of wootz steel, and the bloomery traditions of the Agaria tribes—demonstrate an early mastery of alloy design, heat treatment, and environmental control. These practices reflected not only technological ingenuity but also a nuanced understanding of material properties and sustainability long before these concepts were formalized.

Modern metallurgy in India, marked by the rise of blast furnaces, direct reduction technologies, and the adoption of electric and hydrogen-based processes, builds directly upon this legacy. Innovations such as reactive coke agglomerates, hydrogen-enriched reduction, and the incorporation of waste-derived reductants (e.g., plastics, biomass) illustrate a clear shift toward efficiency, circular economy principles, and low-carbon production. The enduring interest in ancient artifacts, such as the Delhi and Dhar iron pillars, further demonstrates how traditional metallurgical wisdom continues to inspire the development of durable, corrosion-resistant alloys for modern applications.

The dialogue between past and present underscores an important lesson: ancient metallurgical knowledge and cultural practices remain highly relevant to contemporary challenges of sustainability, environmental stewardship, and resource efficiency. By integrating these historical insights with cutting-edge technologies, India's metallurgical sector can not only enhance industrial performance but also position itself as a global leader in sustainable materials science. In conclusion, the journey from ancient bloomery furnaces and wootz crucibles to hydrogen steelmaking and circular economy approaches reflects more than technological progress it represents the continuity of a cultural and scientific tradition that remains central to shaping the future of metallurgy.

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