Environmental Ethics and Sustainable Practices in Traditional Indian Mining and Metallurgy

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Abstract

The spectacular achievements of Indian metallurgy, such as *Wootz* (or "Damascene") steel and corrosion-resistant iron (exemplified by the Iron Pillar in the Qutb Complex, Delhi), are now well known. Pre-Modern India produced a variety of metals on near-Industrial scales, and exported them to many parts of the world. The environmental ethics and sustainable practices underpinning the Indian mining and metallurgy industries, which are notorious for the heavy toll they take on the environment as well as human health, have not received the attention they deserve. Thanks to these practices, India, unlike Europe, preserved its pristine forest cover and biodiversity, despite producing a much larger quantity of metals, and for much longer, whilst having a population of at least an order of magnitude greater. We show that these practices are rooted in Hindu thought, and adherence to them is emphasised in the ancient Hindu texts, including the Vedas and Itihāsas. A study of these practices may prove instructive as the world tries to pivot towards "green" technologies and strategies, and lifestyles congruous with the environment.

Keywords: Traditional Indian metallurgy, Environmental ethics, Sustainability, Sustainable practices, Hinduism, Hindu philosophy

Introduction

Archaeological data about the metallurgical technology of India has come a long way since Smith declared in the early 20th century that India had not had a Bronze Age, and there were no settled cultures in the period between the Stone Age and the historic period.[1] The subsequent discovery of the vast Bronze Age Indus Valley Civilisation, also known as the Harappan Civilisation (2600—1900 BCE), which arose from pre-Harappan cultures and an earlier Neolithic tradition dating back to no later than 6500 BCE forced a fundamental reassessment of the history of the subcontinent. We now have a clearer idea of the trajectory of metallurgical technology on the subcontinent over the millennia, from the earliest use of native gold and copper through the use of bronze, brass, iron and steels, than at any time in the past.

The technical aspects of Indian metallurgy have been studied in considerable detail by scholars of the eminence of Chakrabarti,[2,34,5] Agrawal,[6,7] Biswas,[8] Craddock,[9,10] Sreenivasan,[11–15] and Balasubramaniam.[16–18] Our purpose here is not to attempt another summary of the history of traditional Indian metallurgy. Here, we shall look at some unknown and less-known aspects of Indian mining and metallurgy.

Herein, we shall look at the environmental consciousness that, from the very earliest times, governed mining and metal production, as well as the behaviour of end-users. Indian society was very clearly aware of the deleterious impact of metal production on the environment as well as the health of those involved in mining, smelting and smithy. Consequently, many practices were devised for minimizing this impact, such as reducing demand and recycling metal objects. Metalworkers came up with remarkable scientific innovations to enhance the life of metal objects and ensure that they did not need to be regularly replaced. Western observers from the 18th century onwards frequently tended to describe Indian metal production as inefficient or wasteful, without realizing the larger environmental considerations behind them. For their part, end-users too seem to have been cognizant of their responsibility, and scrupulously recycled virtually all metal in use. This seems to have been the case from the earliest times: when the first Harappan cities were discovered, archaeologists noted that although a very mature metal technology was evident from the earliest levels of occupation, the number of objects found was very small for cities of such large sizes.

Environmental consciousness in Indian thought

There are many injunctions against harming the environment in the ancient texts as well as indications that these were taken very seriously. The opening verse of the Īśa Upaniṣad has been translated as an exhortation that one should be content with what has been allotted to one's share, and give up acquisitiveness and the notion of personal proprietorship.[19] A summary of the guidelines mandating environmental conservation has been published by Sundareswaran.[20] We quote two of the most striking instances from this summary here. In the Ayodhyā Kāṇḍa of the Rāmāyaṇa, when Kauśalyā accuses Bharata of being responsible for Rāma's exile, Bharata breaks down and wishes that he may incur the sin incurred by polluting water (*pānīyadūṣake pāpam*) if there is any truth in Kauśalyā's accusation (Sarga 75,

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verse 55). Trees are also highly valued, for they support an entire ecosystem and are believed to have manifold benefits. Sundareswaran translates the verses 23-31 from Chapter 99 of the *Anuśāsana-parva* of the Mahābhārata as, "As trees propitiate gods by flowers, the manes by fruits, the guests by cool shadow, and as they provide shelter to deva-s, kinnara-s, gandharva-s, rākṣases, and sages, they should be planted on the shores of water reservoirs, it is said. And as they save one from hell (just like a son), trees should be treated just like sons."

This ethos governed the behaviour of the miners and smelters as well as the end-users of metal in India. Metallurgical activity has an inevitable impact on the environment. Mining would have required obtaining ore from forested areas, and often required digging to great depths below the surface. If the mineral deposits were in a forested area, great care would have to be taken to not harm trees in the process of mining. The ore would have to be separated from gangue (the worthless muddy material associated with the useful ore), which could require washing in a running stream. Wood would be required to produce charcoal, which is needed to reduce the ore and smelt metal from it. (Charcoal is produced by burning wood in an oxygen-deficient atmosphere, which removes most of the non-carbon components of the wood as volatile products.) A high production rate of metal shall lead to deforestation.

Impact of mining and metallurgical operations on the environment and on human health

Copper ores usually occur in polymetallic mineralisations, which also contain several heavy metals such as zinc, lead, iron, nickel, cadmium, chromium, manganese, cobalt, mercury, and indeed even copper itself.[21,22] Dust containing these toxic metals is released into the environment during mining operations such as digging and crushing.[23] Washing in streams and rivers that was commonly done to remove mud and clay and obtain a concentrated ore would have resulted in toxic metals contaminating these water bodies.[24] Mining and metallurgical operations also lead to groundwater contamination.[25] Indeed, even today, artisanal and small-scale gold mining is the largest global emitter of the highly toxic mercury.[26] Consequently, the soil in areas close to mines tends to have a higher concentration of these metals, often exceeding the safe limit.[27–31] These metals subsequently enter forage and the food and milk consumed by humans.[32–35] There is an alarming report that heavy metal contamination originating in the Bronze and Iron Ages has persisted in the top soil in the Morvan and Cévennes nature parks in France – which are today regarded as areas of pristine biodiversity free from anthropogenic influence – centuries after mining activity ceased in the region, and that the heavy metals continue to be bioavailable, making their way into the livers and kidneys of wildlife living in the region.[36] Underground mining can cause the formation of sinkholes,[37] and lead to massive spoil heaps being deposited on the surface.

Heating, melting and casting of copper and copper-base alloys also produces vapours of the trace heavy metals present as impurities, or for alloying, in the copper, especially those which have a melting point lower than that of copper (1085°C) such as cadmium (321.1°C), lead (327.5°C), zinc (419.5°C), antimony (630.6°C). Therefore, not only miners and smelters but also those who work in foundries and forges are exposed to heavy metals, that too in a form which makes it easy for the metals to enter their respiratory tracts.[38] Although the metal vapours condense immediately and settle down owing to their weight, some aerosols can remain airborne and even be transported several thousands of kilometres.[39] While some amount of heavy metal aerosols are naturally present in the atmosphere and some particulate load from anthropogenic activity can be tolerated by humans, extensive metallurgical activity has the effect of raising the levels of these aerosols beyond what is safe for health, especially in the vicinity.[40]

Metallurgical activities inevitably involve exposure to these metals, which have been connected with a range of severe health problems including pulmonary and nervous[42] issues, kidney failure,[43] liver impairment and failure,[44,45] cardiovascular diseases,[46] neonatal deformities,[47] and cancer.[48] The harm to health caused by pollution generated by metallurgical activity has been known from a very long time. In the 1st century BCE, Lucretius wrote in his *De natura rerum* that miners had very "unhealthy complexions", and the emissions from gold mines were "poisonous", and Vitruvius noted in his *De Architectura* that streams flowing through mines were harmful.[36] Ancient Indians too appear to have been aware of the adverse environmental impact of mining and metallurgical activities from a very early time. The short lifespan of miners would have been an indication that continuous exposure to minerals was deleterious to health. While there are no records in Indian literature, the British reported the lifespan of miners in the Khetri region to have been only 35—40 years.[2]

Measures adopted in traditional Indian metallurgy for environmental conservation and health

During the Chalcolithic and Bronze Ages, mines were located so far from habitations that archaeologists have not been able to identify the exact deposits that were exploited. Indeed, the oldest known mine in India dates to only 1260 BCE: an ancient borehole running to a depth of over 90 m on the South Lode at the Rajpura-

Dariba zinc-lead mines around 100 km north-east of Udaipur, Rajasthan.[49] This finding indicating that underground mining at a considerable depth from the surface was being done in the region no later than that date. We are left to conclude from lead isotope analysis that the Indus people did indeed exploit the mineral deposits of not just the Aravallis, but also deposits located as far as Waziristan, western Balochistan and even Oman.[50,51] Even during the Mature Harappan Period (2600-1900 BCE), very little metallurgical activity was carried out in or close to the cities. Consequently, there is virtually no material to reconstruct the metallurgical technology of the Indus Valley Tradition with.[52] Thus, we do not know how exactly the Indus people produced their famous casts, such as the Dancing Girl of Mohenjodaro, even though it is obvious they knew closed casting.

Further, unlike many other cultures of the world,[53,54] the Indus people did not leave metallic objects as grave goods, except occasionally, mirrors.[52] In the very first field reports of the excavations of Mohenjodaro (published in 1931)[55] and Harappa (1940),[56] archaeologists noted that, given the size of the cities, the number of metal objects they had found there was unexpectedly small. This, they concluded, was owing to the fact that the occupants of the cities had carefully taken away everything of value, leaving behind what was essentially scrap.[55,56] Further, barring rare hoards secreted away by thieves and forgotten, very little jewellery was found in these cities.[57] This implied that the Indus people handed almost all their metal objects down generations or carefully recycled them.[52] This practice was common all over India till very recently; if a metal object needed to be repaired, the metalsmith would usually do it at a nominal cost, most of which covered any supplementary metal required.

The distant location of mines and metallurgical processing centres to the extent that we do not know anything about the production techniques used, and the deliberate minimising of demand for metal by recycling and handing down generations suggests the Harappans were conscious of the environmental footprint of metal use as well as the adverse impact on health of metallurgical activity, and put in place measures to reduce them to a bare minimum. By reducing their own demand for metal, they would be easing the pressure on miners and smelters to produce more, which in turn would increase their exposure to toxic metals. Considering the abundance of the mineral deposits in their vicinity (the Aravallis and Balochistan), this can only be construed as a conscientious collective endeavour to conserve the environment and lessen the adverse impact on the health of communities engaged in mining and metal-making. Such practices seem to be rooted in the traditional Hindu respect for the environment. On a more practical level, these practices would also provide leeway to the metallurgical community to produce metal for export, as the domestic demand was not very high.

Mining activity was regulated throughout Indian history. Miners had to pay a fee, which was typically proportional to the amount of metal produced in a region. An example of such a fee is the *homla gutta*, levied under the Vijayanagara Empire.[58] This practice appears to have continued into the 19th century, well after the demise of the Vijayanagara Empire, in the form of the fees that iron smelters had to pay the keepers of the forests for collecting wood for producing charcoal, and the village headmen for collecting the ore.[59] Often, the levy to the state could be paid as a portion of the iron produced. It appears that mineral-rich areas in pristine or dense forests were off limits for mining activities. Buchanan reports that there was no mining for iron ore was carried out in the forests of the Western Ghats in spite of the fact that they were very rich in iron ore,[60] even as, in some other areas, local mining operations took great care to confine themselves to the surface and not dig to any depth into the earth and, in the rainy season, did not dig at all and recovered only the ore that was washed down from the hills.[61] It is quite clear the local populace took great care to ensure they did not cause any harm to the environment by pursuing iron smelting as a commercial enterprise driven purely by profit.

Elsewhere, in regions where sub-surface mining was inevitable, Indian miners went to great lengths to ensure that almost all the ore was collected, with very little left behind in waste dumps. On the old copper miners of Singhbhum, a British surveyor observed, “The skill of these ancients is indicated in the manner of their mining. Down to the depth at which they ceased working, usually water level, they have left no workable copper except in the pillars for holding up the walls; they have picked the country as clean as the desert vulture picks a carcass. Looking over some of these old workings it is often remarked that ‘they must have worked over it with tooth picks.’ Even their spoil heaps provide no abundant specimens of copper.”[62]

Today, the amount of ore and its concentration in a deposit are primary factors in deciding if it can be viably extracted. This is owing to the fact that the ore must be separated from the gangue (the sand or mud sticking to the actual ore of interest). This can involve a series of automated steps such as crushing and separation, which add to the processing cost. Further, the separation operations carried out to separate the ore from the gangue may not result in a complete recovery of the ore, and some of it may be lost in the tailings (the waste material left behind after the separation). However, this was not the case in earlier times, when mining and ore dressing was largely manual. Metal-makers of yore frequently exploited deposits that would today be regarded as unviable, and relied on skill to ensure a near-total recovery of useful ore and ensure a decent output of metal. Indeed, it may be altogether wrong to use present-day criteria to estimate if a metal may have been produced in a region in the past. For instance, European scholarship has always held that India could not have had a full-fledged Bronze Age as it is not well-endowed with deposits of tin. Thus, it is never considered an exporter of bronze objects, even if the weight of the evidence suggests otherwise.[62] In fact, we have decisive evidence from lead isotope analysis that not only was India producing tin by exploiting some local deposits by no later than then 3rd millennium BCE, but was also exporting them to other contemporaneous cultures of West Asia.[63] This was clearly made possible by the tendency of domestic demand staying very low, thanks to the practice of recycling metallic objects mentioned above. The fact that the subcontinent was tin-deficient is obvious from the fact that pure and arsenical copper, as well as tin-bronze were used for making similar items at all levels of occupation in the Indus Valley tradition. Nevertheless, the subcontinent was not only a net exporter of bronzes through the Bronze Age, but was sending large shipments of tin ingots to West Asia from the Peninsular coast in the 1st millennium BCE.[64]

The tendency of iron to rust, thereby severely and rapidly compromising the integrity of the objects fashioned out of it, must have been a huge concern for early iron makers. Not only was there an environmental cost in terms of the charcoal (wood) required and the disruption caused by mining, but the short life and poor reliability of rust-prone iron products were not at all commensurate with the effort which went into producing them. Hence, the early iron makers of India may have embarked on a quest for ways for rust-proofing iron. Observant tourists may have noted the near-impeccable condition of the numerous iron cannons in the forts built by the Marathas on India's west coast in the 17th and 18th centuries, or elsewhere in the country such as Mehrangarh (Jodhpur, Rajasthan) and Golconda (Hyderabad, Telangana). These guns have been in the open for over two centuries now, yet do not show any signs of the severe rusting and corrosion that can be expected from exposure to rainfall.[65] Indian iron makers also developed a form of corrosion-resistant iron that can last many centuries. The Mehrauli pillar is a much better known illustration of this "rust-less" iron. Lesser known examples are the iron framework of the Konark Temple, the fragmented iron pillar of Dhar, which is nearly three times the length of the Mehrauli pillar, and the iron pillar for lighting lamps outside the Mookambika Temple in Kollur, Karnataka. As the technology for making this corrosion-resistant iron had been mastered by the 4th century CE itself, as demonstrated by the Mehrauli pillar, it is reasonable to conclude Indian iron makers had strived for developing it from very early times. Eliminating the need for repeated replacement every few years resulted not only in savings in terms of the effort required for producing the additional iron but also reducing the adverse environmental impact of the extraction and smelting processes.

Comparison with Europe

The conservation of forests and wildlife in India[66] contrasts sharply with the situation in Europe, where increasing demand for metal combined with expansion of agriculture led to severe deforestation and a dire lack of wood by the early 16th century.[67–69] As a result of deforestation, there was also a loss in biodiversity, and many species of animals like the moose and European bison, and most large carnivores were driven completely or nearly to extinction.[70–72] It was to overcome the severe shortage of wood that Europe turned to coal as a fuel, which eventually became the mainstay of the Industrial Revolution.[73] However, wood, and charcoal derived from wood, are carbon-neutral: wood is produced by fixing the carbon dioxide present in the atmosphere; hence, burning of wood or charcoal contributes no net emissions to the atmosphere, and it is naturally replaced. Coal, on the other hand, produces net carbon dioxide, which is a greenhouse gas, when it is burnt, which would not have been released into the atmosphere if the coal had not been mined and used as fuel. Atmospheric carbon dioxide levels have risen from around 270 ppm to 400 ppm since the Industrial Revolution.[74] Carbon dioxide emissions have been held responsible for global warming and climate change.[75,76]

What is remarkable is that this rapid and extreme deforestation was brought about even as Europe was not capable of producing the range of alloys that had already been in common use in India for more than a millennium by then. Even in the latter half of the 20th century, by when a great deal of traditional knowledge was irretrievably lost, large traditional furnaces capable of producing up to 40 kg of iron per heat were in operation in Nagpur, in the Vidarbha region of Maharashtra, and many tribes such as the Agarias, Mundas and Asuras living in the states of Uttar Pradesh, Jharkhand, Odisha and Chhattisgarh were able to recreate their traditional iron smelting operations that produced up to 100 kg of iron a day. It is possible that batteries of such large furnaces were used to produce the huge quantities of iron that went into the manufacture of large objects.[77] It is estimated that, in the mid-19th century, the Khasi Hills region of Meghalaya produced around 2000 tonnes of iron annually, most of which was traded to other regions and exported along the traditional trade routes.[78] Similarly, the technology for producing zinc was unknown, and consequently, brass was virtually unknown in Europe[79] till William Champion reverse-engineered the traditional Indian downward distillation process for smelting zinc in the late 18th century CE.[10,80] Metallic zinc had been isolated in India by the 4th century BCE,[49] and it has been estimated that, between the 13th and 18th centuries CE, the Zawar mines in Rajasthan may have produced around 1 lakh tonnes of zinc,[81] which may well be regarded as industrial-scale production. What is more, the quality of Indian steels, especially the *wootz* or so-called Damascene, was not matched outside the subcontinent. Wootz steel was imported in very large quantities by the Arabs for making swords and armour, and it is likely mediaeval Europeans had first encountered this steel during the Crusades.[82] High carbon steels were being produced in India by the earliest 1st millennium BCE, as suggested by a steel ring containing 0.8% carbon found at the Megalithic site of Kadebakele on the banks of the Tungabhadra in Karnataka.[83] By the 3rd century BCE it was known as far as the Greek world that the Indians used a crucible process for making high carbon steels,[84] which was responsible for their name, “crucible steels”. In the late 17th century, before the start of the Industrial Revolution in Europe, ingots of wootz steel for making Damascene swords were being produced at nearly an industrial scale and shipped to Persia.[82] There were many centres for the production of wootz steels all over India, including Lahore, Amritsar, Agra, Jaipur, Gwalior, Tanjore, Mysore and Golconda, none of which survive today.[82]

The preference for small-scale, labour intensive processes may deceive one into believing that Indian metalsmiths were content not to explore scaling up to an industrial scale. We have evidence that this was not so. Based on archaeological evidence of old furnaces dating from the 4th century BCE discovered in Samanalawewa in southern Sri Lanka, Gill Juleff was able to reconstruct wind-powered furnaces that were able to smelt iron as well as produce high-carbon steels.[85] The furnaces were built on the western margins of hill-tops and ridges, so as to be normal to the incident wind. The flow of wind over the top of the furnace created a steep pressure drop down the elevation of the furnace wall, creating suction which drew the wind into the furnace through tuyeres built into the lower part of the front wall. This draft generated the temperatures necessary for the smelting operation, enabling the production of low-carbon iron similar to that produced by bellows-assisted forced-draught bloomery furnaces, with the added advantage that the draft in this case was continuous and did not require manual labour to induce. The furnace design was also to nullify the effect of wind gusts. The process could be scaled up by building furnaces of higher capacities with increased lengths, as was done in subsequent periods. This leads Juleff to describe them as “linear furnace technology”. This technology, which exploited hydrodynamic principles to obviate manual bellowing, may be among the earliest examples of mechanisation in the world. Further, apart from the smelting and carburization process itself, the mechanisation itself relied entirely on wind energy, which is clean and renewable. The ingenious use of hydrodynamic principles in this instance also raises the reasonable question if hydrodynamic and pneumatic principles were exploited for mechanisation in ancient India.

Remarkably, almost half of the metal produced in the reconstruction trials were found to be slag-free high-carbon steel. Although this indicated heterogeneous carburization, it also showed that the furnaces could be used to produce high-carbon steels on an industrial scale, which may account for the Sri Lankan *Sarandibi* steel attested in Islamic literature. This clean, wind-powered technology reached a maximum in the 9th century CE, before vanishing in the 11th century. Similar furnaces from the Historical Period were also discovered in the nearby village of Kosgama, and in Sigiriya in the Central Province, indicating that this technology may have been widespread.[86] Strikingly, the Sigiriya furnaces appeared to have been mounted by tapering shafts, and probably relied on the draft induced by hot gases rising from the furnace to augment the draft created by the wind. This is evidence that linear technology could be tailored with innovations to suit local conditions.

Conclusion

We have seen how the environmental consciousness of traditional Indian metallurgy as far back as the Indus Civilisation is based in the deep sense of responsibility towards the environment expressed in the Upaniṣads and the Epics. We also saw how Indian metallurgy came up with many remarkable engineering innovations within the ambit of the principles of ecological conservation to expand the life and range of its products, even as it kept its environmental footprint to a minimum. This ensured the preservation of the environment, and flora and fauna even as the subcontinent produced several tonnes of useful metals annually for many millennia, which were not only used domestically but also exported to many parts of the world. These practices hold useful lessons for the modern metal production industry, which is a major contributor to environmental pollution, as well as consumers in general as we strive to reverse climate change and the deleterious effects of the degradation of ecosystems worldwide.

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