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RESEARCH ARTICLE

SCIENCE AND TECHNOLOGY IN ANCIENT INDIA: A HISTORICAL REVIEW AND ITS CONTEMPORARY RELEVANCE

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ABSTRACT

India has a rich and lasting tradition of scientific and technological achievement spanning mathematics, astronomy, metallurgy, medicine, civil engineering, and organized higher education since ancient times. The paper examines five domains in science and technology viz. t*he mathematical and astronomical development* through the contributions of Aryabhata, Brahmagupta, and their successors; *the metallurgical development*; *the surgical and anatomical knowledge*; *the urban planning and hydraulic engineering* of the Indus Valley Civilization; and the *institutionalized learning* as reflected by Nalanda and Takshashila. The paper explores literature of archaeometallurgical studies, medical history, and the history of mathematics, and found that these achievements were the product of sustainable, collective learnt traditions that combined empirical observation, systematic documentation, and sharing of ideas across people of different generations. It is further reflected how these knowledge traditions diffused to the Islamic world, China, and Europe, shaping the global history of science. Implications for contemporary relevance in indigenous knowledge systems are discussed.

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INTRODUCTION

The history of science is often described in terms of achievements passing from Mesopotamia and Egypt to Greece and Rome to modern Europe, often tends to marginalize the sustained indigenous scientific traditions of South Asia including India. Yet from the urban engineering of the Indus Valley Civilization in the third millennium BCE to the mathematical astronomy of the Gupta period and beyond, the Indian subcontinent generated technological and scientific knowledge that was both locally transformative and globally influential. Ancient India was a major centre of knowledge where several natural and pure sciences developed alongside remarkable achievements in art, architecture, literature, and philosophy, with scholars contributing significantly to biology, medicine, astronomy, and mathematics (Testbook, n.d.). Five domains are examined in which the scientific and technological achievements of ancient India are best documented and most rigorously studied by contemporary scholarship viz. *mathematics and astronomy; metallurgy and materials science; medicine and surgery; urban planning and hydraulic engineering; and organized higher education*. The Gupta period (4th–6th century CE) is frequently identified as a golden age of ancient Indian science particularly in astronomy and mathematics (Testbook, n.d.). The effects of Indian scientific knowledge extend considerably later, through the transmission of Indian numerals and medical knowledge to the western world. The paper proceeds thematically to fulfil the following objectives:

- To summarize the achievements and the historical sourcing of the principal areas of ancient Indian science and technology — mathematics and astronomy, medicine and surgery, metallurgy and materials science, urban and civil engineering, and the institutions of higher learning that supported this work.
- To consider the empirical character of ancient Indian science and its global diffusion for the contemporary relevance of science.

Mathematics and Astronomy: Ancient Indian mathematics and astronomy evolved as part of a tightly linked scholarly tradition in which numbers, geometry, trigonometry, calendrical calculation, and planetary astronomy were practiced and theorized together rather than as separate disciplines (Singh, 2026). Within this tradition, Aryabhata stands as the earliest Indian mathematician whose work and biography are available to modern scholars in detail (Hyashi, 2026).

Believed to have been born in 476 CE and to have worked at Kusumapura, near present-day Patna, Aryabhata composed the Aryabhatiya around 499 CE, a text that blended mathematics and astronomy in verse form (Hyashi, 2026). The Aryabhatiya is organized into four sections viz. *Gitikapada, Ganita, Kalakriyapada, and Golapada*. These four sections cover foundational mathematical concepts, arithmetic and algebra, time reckoning, and celestial spheres, respectively (Dubey, 2025). Within these sections, Aryabhata provided geometrical rules, sine tables, methods for solving indeterminate equations, models of planetary motion, and theories of eclipses, and he proposed that the apparent daily rotation of the stars results from the rotation of the Earth on its axis (Singh, 2026). He is also credited with an early approximation of pi and with methods for calculating square and cube roots (Thomas, n.d.). Remarkably, Aryabhata treated midnight, as the start of each astronomical day, a convention that distinguished his school from other contemporary systems (Dubey, 2025; Hayashi, 2026).

Aryabhata influenced the later mathematicians and astronomers, including Bhaskara I, Brahmagupta and Bhaskara II, preserved, disputed, and extended his work to the most sophisticated pre-modern mathematical traditions in the world (Singh, 2026). Brahmagupta, writing in the 7th century, made a particularly consequential contribution: in his *Brahmasphutasiddhanta* of 628 CE, he became the first mathematician known to define zero as a number in its own right and to state formal rules for arithmetic operations involving zero, positive numbers, and negative numbers on equal footing (Dutta, 2022). This work is the earliest surviving text to give a detailed exposition to zero (Dutta, 2022), and it established zero not merely as a place in the number notation system but as an abstract quantity subject to defined arithmetic laws. The decimal place-value system that underlies virtually all modern computation was likewise developed in India, with place number notation for an empty position started as early as the 3rd century BCE and full decimal place value in mathematics by the early first millennium CE (Plofker, 2025). This numeral system, together with the conception of zero, spread outward through trade and scholarly contact: Arab mathematicians, including al-Khwarizmi, studied and transmitted Indian mathematical texts, and by the 12th century the Hindu-Arabic numeral system had displaced Roman numerals across much of Europe (Plofker, 2025). Later figures in the tradition, such as Bhaskara II, who directed the astronomical observatory at Ujjain in the 12th century, extended this work further contributingto formalizing the modern sign convention and was the first one to statethat dividing a number by zero yields infinity (Plofker, 2025). *Metallurgy and Materials Science:* Ancient Indian metallurgists achieved a level of technical sophistication in iron and steel production that remains a subject of active scientific investigation. Bloomery iron production in India is traceable to approximately 1200 BCE, and the traditional knowledge associated with this craft survives among Adivasi (tribal) communities such as the Agaria to the present day (Balasubramaniam *et al*., 2015). The most celebrated artifact of this tradition is the Iron Pillar of Delhi, dated to the reign of Chandragupta II in the early 5th century CE (Balasubramaniam *et al*., 2015; The Archaeologist, 2026). The pillar carries a Sanskrit inscription in Brahmi script and has remained largely free of rust for over 1,600 years despite continuous exposure to the open air and monsoon climate of Delhi (The Archaeologist, 2026). Extensive materials-science research, much of it conducted by R. Balasubramaniam and colleagues at the Indian Institute of Technology Kanpur, has linked this corrosion resistance to the pillar's unusually high phosphorus content, which promotes the formation of a thin, adherent, protective passive film on the metal surface (Balasubramaniam *et al*., 2015). This composition-microstructure relationship reflects a smelting and forging process, still practiced by traditional Indian blacksmiths, that differs fundamentally from the fluxed, low-phosphorus processes that came to dominate later Western ironmaking (Balasubramaniam *et al*., 2015). A 2021 study using correlative microscopic, spectroscopic, diffraction, and tomographic techniques examined iron produced by the Agaria tribes of Chhattisgarh using traditional methods and confirmed that both furnace smelting conditions and a subsequent hot-hammering (forging) step are critical to corrosion resistance (Dwivedi *et al*., 2021). The hammering process consolidates internal pores and removes slag inclusions, producing a thicker, more protective corrosion-product layer than is observed in un-hammered iron (Dwivedi *et al*., 2021). This research demonstrates that the durability of artifacts such as the Delhi Iron Pillar is attributable to a deliberate, replicable metallurgical process rather than to chance or unusual raw materials alone. Ancient India was also the source of wootz steel, a high-carbon crucible steel produced by melting iron together with carbon-rich material in a sealed crucible, yielding a metal prized for its hardness, flexibility, and ability to take and hold a sharp edge (Dwivedi *et al*., 2021; Curriculture,2025). Wootz steel, exported from South India for over a millennium, provided the raw material later worked into the legendary Damascus blades of the Middle East (Curriculture,2025). Modern metallurgical studies using electron backscatter diffraction and related techniques have examined surviving wootz blades to characterize the ultra-high-carbon microstructures, carbide banding, and thermomechanical processing that gave the steel its distinctive properties (Balasubramaniam *et al*., 2015). Indian metallurgists of this period also operated zinc-distillation furnaces at Zawar in present-day Rajasthan, among the earliest known sites of zinc production anywhere in the world, dating to around 400 BCE and Postlethwayt'sUniversal Dictionary of Trade and Commerce, London, 1751 still wasn't aware of how Zinc was produced (Craddock *et al*, 1985). The *Rasaratna Samuchaya* (800 CE) explains the existence of two types of ores for zinc metal, one of which is ideal for metal extraction while the other is used for medicinal purpose (Biswas, 1993). It also describes two methods of zinc distillation (Craddock *et al*, 1985).

Medicine and Surgery: Ayurveda, the traditional system of medicine that emerged in the Vedic period (c. 2500–1000 BCE), forms one of the most extensively documented branches of ancient Indian science (Raveenthiran, 2011). Its two foundational texts are the Charaka Samhita, which addresses internal medicine and includes an oath of professional conduct comparable to the Hippocratic Oath, and the Sushruta Samhita, which is distinguished by its unusually detailed treatment of surgery, surgical instruments, and surgical training (Loukas *et al*., 2010; Sushruta Samhita, n.d.). While the relative chronology of the two texts remains debated among historians, the Sushruta Samhita is conventionally associated with the physician Sushruta, who is said to have studied under Divodasa, the king of Varanasi (Sushruta Samhita, n.d.). The Sushruta Samhita is organized into six sections viz. *Sutrasthana, Nidanasthana, Sharirasthana, Chikitsasthana, Kalpasthana, and Uttaratantra*.

Table 1. Key Figures and Contributions in Ancient Indian Mathematics and Astronomy

Scholar	Approx. Period	Major Work	Key Contribution
Aryabhata	b. 476 CE	Aryabhatiya (c. 499 CE)	Place-value foundations, sine tables, Earth's rotation, eclipse theory
Brahmagupta	598–668 CE	Brahmasphutasiddhanta (628 CE)	Formal arithmetic rules for zero and negative numbers
Bhaskara I	7th century CE	Mahabhaskariya, Laghubhaskariya	Commentary and extension of Aryabhata's astronomy
Bhaskara II	1114–c. 1185 CE	Lilavati, Bijaganita, Siddhanta Shiromani	Sign conventions, division by zero yields infinity, algebraic methods
Mahavira	9th century CE	Ganita-sara-sangraha	Jain-influenced compendium of arithmetic operations

Table 2. Comparative Overview of Ancient Indian Metallurgical Achievements

Artifact/Product	Approx. Date	Key Property	Underlying Mechanism
Delhi Iron Pillar	c. 400–415 CE	Long-term corrosion resistance	High phosphorus content forming protective misawite passive film
Agaria tribal iron	Traditional/ongoing	Enhanced corrosion resistance vs. modern iron	Bloomery smelting plus hot hammering to remove slag/pores
Wootz (crucible) steel	c. 500 BCE onward	High hardness and edge retention	Ultra-high-carbon microstructure from controlled crucible melting
zinc distillation at Zawar	From c. 400 BCE	Among the earliest known sites of zinc smelting in the world	

Table 3. Structure and Scope of the Sushruta Samhita

Section (Sthana)	Focus	Illustrative Content
Sutrasthana	Fundamental principles	General surgical doctrine and ethics
Nidanasthana	Pathology and etiology	Disease classification and causation
Sharirasthana	Anatomy and embryology	Cadaveric dissection method; skeletal enumeration
Chikitsasthana	Therapeutics	Wound healing, fracture management, reconstructive procedures
Kalpasthana	Toxicology	Poisons, antidotes, and pharmaceutics
Uttaratantra	Specialized branches	Ophthalmology, pediatrics, ENT, psychiatry

These cover fundamental principles, pathology, anatomy and embryology, therapeutics, toxicology, and specialized subjects such as ophthalmology and paediatrics (Raveenthiran, 2011). In total, the text consists of 184 chapters that describes some 1,120 diseases and 700 medicinal plants, and talks about eight categories of surgical operation (Ahmed, 2026). Sushruta is widely credited as an early pioneer of plastic and reconstructive surgery, and the text describes procedures for nasal reconstruction (rhinoplasty) using a forehead flap, a technique whose basic principle continues to inform modern reconstructive practice (Sushruta Samhita, n.d.). Beyond reconstructive procedures, the Sushruta Samhita documents cataract couching—a surgical technique for displacing the clouded lens of the eye to restore vision—that was apparently unknown to surgeons elsewhere in the ancient world at that time (Shah, 2018). Sushruta clearly recommended that students prepare and dissect a body in order to gain firsthand anatomical knowledge before undertaking surgical training, a methodological approach that describe him as among the earliest recorded anatomists (Gandhi & Patil, 2024). The Sushruta Samhita mentions 300 bones in the body according to its surgical tradition, in contrast with the 360 described by general Ayurvedic texts of the period (Sushruta Samhita, n.d.). Detailed clinical descriptions embedded in the text have prompted comparisons with modern nosology – a branch of medical science that deals with classification of diseases. For example, an analysis of the condition termed *baddha-gudodaram*in the Sushruta Samhita found close correspondence with what is now recognized as Hirschsprung disease (congenital megacolon), including a described palliative procedure resembling a modern sigmoid colostomy (Raveenthiran, 2011). Ayurvedic etiology in the Samhita attributed such disorders due to the imbalance among three gunas—vaat, pitta, and kapha, —a tridoshic framework that organized diagnosis and treatment corresponding to processes governing the body (Raveenthiran, 2011).

Urban Planning and Hydraulic Engineering: The Indus Valley Civilization (c. 3300–1300 BCE) represents one of the earliest urban cultures to display a systematic andlogical approach to city planning and water management system (Pharswan& Badoni, 2025). Excavations at Mohenjo-daro, Harappa, and Dholavira reveal cities built on grid-based street layouts, with roads frequently intersecting at right angles and residences constructed from standardized, kiln-fired bricks (Kanneboina & Singh, 2022). Harappan cities are particularly known for their well-established sanitation system. Streets were equipped with covered drains that carried wastewater away from residential areas, and many individual houses were connected to this citywide drainage network, reflecting a civic commitment to public health (Kanneboina & Singh, 2022). The Great Bath at Mohenjo-daro, a large carefully waterproofed public tank acts as evidence to the civilization's mastery of hydraulic construction (Kanneboina & Singh, 2022). At Dholavira, archaeologists have documented an extensive system of reservoirs, step-wells, and channels engineered to harvest and store monsoon runoff, ensuring water availability through the dry season (Pharswan& Badoni, 2025). It was found that water management system in Indus valley was scientific as it was governed by basic hydraulic principles; gravity, pressure differentials, and hydraulic gradients to route wastewater efficiently and to control seepage from storage reservoirs (Pharswan& Badoni, 2025). Settlements were also frequently sited on elevated platforms or mounds, a practice that reduced flood risk and indicates that Indus planners were attentive to local hydrological and ecological conditions (Asghar *et al*, 2026).Gently sloped drainage channels made use of gravitational flow to keep wastewater moving and minimize stagnation and contamination, while well and reservoir construction reflected an experimental understanding of capillary action and hydrostatic behavior (Pharswan& Badoni, 2025).

Beyond domestic infrastructure, large-scale granaries—substantial structures built on raised, damp-resistant foundations and equipped with ventilation ducts—served as storehouses for surplus agricultural grain and were typically positioned near residential and commercial zones, indicating a planned relationship between food storage and urban economic organization (Halemani, 2024). Taken together, the drainage systems, standardized construction, water-harvesting infrastructure, and granary placement documented across Harappan sites point to a civilization capable of coordinated, large-scale civic planning grounded in practical engineering knowledge, even though the Indus script has not yet deciphered that might provide a detailed explanation on various accounts (Halemani, 2024).

Centres of Learning: Nalanda and Takshashila: The scientific and technical achievements described above did not emerge in isolation; they were sustained and transmitted through organized institutions of higher learning. Takshashila (Taxila), located in what is now northwestern Pakistan, is regarded as among the oldest centres of higher education in the ancient world, with roots extending back to approximately the 6th to 7th century BCE (Dodiya, 2022). Its curriculum spanned scripture, statecraft, medicine, and the arts, and it is traditionally associated with Chanakya, author of the Arthashastra, an early account on governance and political economy (Verma, 2026a).

Nalanda, founded in present-day Bihar during the 5th century CE under the Gupta dynasty and flourished under later rulers including Emperor Harshavardhana, developed into one of the first major residential universities in world history (Teachers Institute, 2026). Contemporary accounts, describe a rigorous admissions process in which students are examined before entry, with only a minority of applicants ultimately admitted, after which education was provided without charge (Teachers Institute, 2026). The Tibetan scholar Taranatha later described Nalanda's library complex, the *Dharmaganja*, as a nine-story structure, reflecting the scale of the institution's manuscript holdings (Hindu Dharma Shodh Sansthan, 2026). The curricula of both institutions extended well beyond religious study to include mathematics, astronomy, medicine, logic, and linguistics, and both attracted students and scholars across Asia, including China, Korea, Tibet, and Central Asia (Dil Se Bharat, n.d.; Verma, 2026a). Instruction relied heavily on organized debate and dialogue between teacher and student, a pedagogical model that enables the student to defend and improve an argument rather than on rote memorization (Dil Se Bharat, n.d.). Within thirty years of Xuanzang's visit, the famous Buddhist monk from China in 7th century, at least eleven additional Chinese and Korean travellers are recorded as having journeyed to Nalanda, illustrates its scholarly reputation across different countries (Teachers Institute, 2026). It was through such centres, and the networks of trade and pilgrimage that connected mathematical, medical, and metallurgical traditions to the wider region, and Indian scientific and technical knowledge was preserved, extended, and eventually transmitted beyond the subcontinent (Teachers Institute, 2026).

Relevance in Contemporary Times: The scientific and technological achievements of ancient times are not merely of few people'sinterests in gathering and preserving historical documents and artefacts, several have direct and traceable links to present-day mathematics, medicine, materials science. Several themes cut across the domains reviewed here.

Mathematics & Computing: First, ancient Indian science was cumulative and self-correcting; successive scholars in the mathematical-astronomical tradition, from Aryabhata through Bhaskara II, did not simply repeat their predecessors' claims but tested, disputed, and extended them across centuries of thoughts andreflections (Singh, 2026). Every measurement, financial calculation, and item of scientific notation in use today depends on place-value notation, and the binary logic that underlies digital computing is itself built on the conceptual foundation of a defined zero as a genuine numerical value rather than an absence of value (Pant, 2026). The decimal place-value system and the concept of zero moved from India into the Arab world and then into Europe through documented channels of scholarly contact, including the translation of Sanskrit astronomical texts into Arabic as early as the 9th century (Hyashi, 2026; Plofker, 2025).

Materials Science and Sustainable Engineering: Several of these achievements were subjected to independent, non-Indian scientific verification only in recent decades, which underscores both their superiority and the historical neglect they suffered in earlier Western historiography of science. The corrosion resistance of the Delhi Iron Pillar continues to attract attention from metallurgists interested in low-alloy, phosphorus-based corrosion protection as an alternative to modern coatings and stainless-steel alloying strategies, since replicating the pillar's specific microstructure at industrial scale remains difficult (Raj *et al*., 2005; Balasubramaniam *et al*., 2015; Dwivedi *et al*., 2021).

Non-destructive metallurgical analysis has shown that this resistance results from the iron's unusually high phosphorus content combined with the absence of sulfur and manganese, which promotes the formation of a thin, self-healing passive layer of iron hydrogen phosphate hydrate on the metal's surface (Raj *et al*., 2005). Since comparable phosphorus-rich, corrosion-resistant iron has also been documented in other Gupta-period artifacts, including iron clamps from temples and iron beams at the Konark's Sun Temple which shows the process not accidental but a deliberate smithing process (Satyendra, 2013). The water-sensitive, drainage-oriented urban design of Indus Valley cities represents sustainable urban planning and climate-resilient infrastructure, as it lay emphasis on decentralized household sanitation, standardized construction, and integrated water management (Wright, 2022)

Medicine, Ayurveda, and Global Health Practice: Likewise, clinical-historical analyses of the Sushruta Samhita have identified descriptions consistent with conditions such as Hirschsprung disease centuries before their formal identification in Western medicine (Raveenthiran, 2011).A comparable pattern appears in the medical tradition, where the Sushruta Samhita's emphasis on direct anatomical observation through dissection reflects a broadly empirical orientation rather than reliance on doctrine alone (Loukas *et al*., 2010). Concepts first systematized in the Sushruta and Charaka Samhitas hasenlightened contemporary medical and wellness practice. Reconstructive surgeons and medical historians regularly cite Sushruta's forehead-flap rhinoplasty technique as a conceptual ancestor of modern pedicled skin-flap reconstruction, and Ayurveda more broadly has become a globally practiced complementary medical system, formally institutionalized within India's public health administration through a dedicated government ministry and pursued as a subject of ongoing pharmacological and clinical research (Champaneria *et al*., 2014). At the same time, historians of medicine caution against uncritically presenting every ancient technique as a direct equivalent of its modern counterpart; the value of this history lies in accurately tracing conceptual lineage rather than in overstating technical continuity.

Education Policy and National Identity: Institutions such as Nalanda served simultaneously as repositories of accumulated knowledge and as nodes through which that knowledge was transmitted outward via visiting scholars and pilgrims (Teachers Institute, 2026). Nalanda functioned for around millennium, from 427 CE until its destruction in the twelfth century, and its international reach have led some scholars to describe the fifth and sixth centuries CE, the period under the Gupta dynasty as a golden age of Indian knowledge systems (Ingalls, 1976). These findings carry implications beyond antiquarian interest. They complicate diffusionist narratives that locate the origins of modern science primarily in the Mediterranean and early modern Europe, and they suggest that indigenous technical traditions—such as the ironworking knowledge still practiced by Agaria communities—may retain practical insights relevant to contemporary materials science and corrosion engineering (Dwivedi *et al*., 2021). This scientific heritage occupies a prominent place in Indian public discourse and national identity, which brings both benefits and risks: it can motivate interest in STEM education and provide a genuine appreciation to non-Western contributions, but it can also encourage overstated or outdated claims when historical achievements are not subjected to scientific analysis through a modern lens. Caution has to be warranted: dating many ancient Indian texts and artifacts remains contested, oral and manuscript transmission introduces uncertainty into the historical record, and modern retrospective diagnoses of ancient medical descriptions necessarily involve interpretive judgment (Sushruta Samhita, n.d.).

Traditional Knowledge and Biopiracy Disputes: Number of instances of "biopiracy" has also been seen in the past. In a response to that India has developed a Traditional Knowledge Digital Library (TKDL), a searchable, multilingual database that translates traditional Ayurvedic, Siddha, Unani, and yoga-based formulations into a classification format compatible with the International Patent Classification system used by patent offices worldwide (Fredriksson, 2021). Scholars analyzing the TKDL note that it is not without limitations. It documents only a portion of India's traditional knowledge and mentioned only textually recorded traditions over oral ones but it however illustrates a direct, practical link between ancient Indian textual knowledge and contemporary global intellectual-property governance (Fredriksson, 2021).

CONCLUSION

The scientific and technological record of ancient India—spanning the decimal numeral system and the mathematics of zero, the metallurgy of the Delhi Iron Pillar and wootz steel, the surgical and anatomical knowledge of the Sushruta Samhita, the hydraulic engineering of the Indus Valley cities, and the institutionalized scholarship of Nalanda and Takshashila—reflects a coherent and cumulative intellectual tradition rather than a sequence of isolated interests. Contemporary scientific analysis continues to validate and extend understanding of these achievements, from materials-science explanations of ancient corrosion resistance to clinical-historical readings of Ayurvedic surgical texts. As global scholarship increasingly recognizes multiplecentres of scientific development in the ancient world, the case of ancient India's achievements offers a well-documented and still-active field of inquiry, one in which archaeological, textual, and laboratory-based methods continue to yield new insight into a tradition whose effects are still measurable in modern mathematics, medicine, and engineering.

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