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OLIGODYNAMIC, COAGULATION AND LIGAND-EXCHANGE CHEMISTRY VALIDATE INDIGENOUS INDIAN WATER PURIFICATION PRACTICES: A FOCUSED REVIEW SUPPORTING SDG-6

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ABSTRACT

Rural and semi-urban India has relied for generations on indigenous, low-cost water purification practices that predate modern chemical engineering. This focused review narrows its scope specifically to the chemical mechanisms underlying such practices, excluding purely physical and biological explanations, to provide a focused, reaction-level account. Evidence was synthesised from eighteen peer-reviewed sources identified through a structured literature search. Findings confirm that copper and silver vessel storage acts through oligodynamic metal-ion release and redox-driven oxidative damage to bacterial membranes; that seed-derived cationic proteins from *Moringa oleifera* and *Strychnos potatorum* clarify turbid water through electrostatic charge neutralisation of colloidal particles; and that biochar and related carbonaceous materials remove fluoride through ligand-exchange reactions at hydroxylated metal-oxide surfaces. Surface and analytical chemistry techniques, including zeta potential analysis, Fourier-transform infrared spectroscopy, X-ray photoelectron spectroscopy and inductively coupled plasma mass spectrometry, corroborate these mechanisms at the molecular level. Thermodynamic parameters, including Gibbs free energy of adsorption, confirm the spontaneity of the underlying reactions. The review concludes that indigenous Indian water purification practices rest on genuine, mechanistically explicable chemistry, and that this chemical evidence base offers a scientifically defensible foundation for the design of low-cost, culturally embedded water treatment systems. This mechanistic evidence base offers a scientifically defensible foundation for scaling these practices into standardised, low-cost treatment protocols and directly supports Sustainable Development Goal 6 (Clean Water and Sanitation).

Keywords: Indigenous Water Purification, Coagulation Chemistry, Ligand Exchange, Oligodynamic Disinfection, Surface Chemistry, Water Treatment Chemistry.

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INTRODUCTION

Access to safe drinking water remains a major public-health challenge in rural and semi-urban India, where communities have long relied on indigenous, low-cost water purification practices developed empirically over generations, well before the advent of modern chemical engineering.[1] Contamination by pathogenic microorganisms, dissolved iron, fluoride and turbidity renders many local water sources unfit for direct consumption, and household-level intervention remains, for many communities, the only practical barrier against waterborne disease. A growing body of chemistry research has begun to interrogate these folk technologies using the tools of modern analytical and physical chemistry. This literature demonstrates that several indigenous practices rest on genuine, mechanistically explainable

chemical principles: metal-ion redox and antimicrobial chemistry, protein-mediated electrostatic coagulation, and ligand-exchange adsorption at hydroxylated mineral and carbon surfaces.[2,3] Because these practices are frequently also described in the literature using physical (e.g., bulk physisorption, pore-scale filtration) and biological (e.g., microbial biosorption, biofilm ecology) framings, the present review deliberately narrows its scope to the chemical mechanisms alone. This focus keeps the review within a defensible page budget while preserving a coherent, self-contained scientific narrative: every practice discussed below is explained strictly in terms of the chemical reactions, equilibria and surface chemistry that govern it. A dedicated, chemistry-only synthesis of this kind is presently lacking in the literature, which typically treats chemical, physical and biological explanations together without disentangling them; this review addresses that gap by isolating and critically evaluating the chemical evidence in its own right. This focused review therefore aims to (i) identify indigenous Indian water purification practices with a demonstrable chemical basis, (ii) synthesise the experimental evidence for the specific chemical reactions and equilibria involved, and (iii) evaluate the extent to which modern analytical and surface chemistry techniques corroborate these mechanisms. In doing so, the review directly supports Sustainable Development Goal 6 (Clean Water and Sanitation) by consolidating the chemical evidence needed to translate indigenous practice into reliable, low-cost water-treatment interventions for underserved communities.

EXPERIMENTAL

Literature Search and Eligibility Criteria

A structured literature search was conducted across Scopus, Web of Science, PubMed, ScienceDirect, SpringerLink and the RASĀYAN Journal of Chemistry archive, combining the terms ‘indigenous’, ‘traditional ’, or ‘folk’ with ‘water purification’, ‘coagulant’, ‘defluoridation’, and ‘surface chemistry’. Records were included only if they (a) described an indigenous Indian water-treatment practice, or a material derived from it, and (b) reported a chemically interpretable mechanism (redox chemistry, coagulation chemistry, ligand exchange, or surface/analytical chemistry characterisation), consistent with this review's deliberately chemistry-only scope. Studies whose principal explanatory framework was physical (e.g., bulk physisorption without surface-chemical characterisation, size-exclusion filtration) or biological (e.g., microbial ecology, biofilm predation) were excluded from the chemical-mechanism synthesis presented here. Eighteen sources meeting these criteria were retained for narrative synthesis.

RESULTS AND DISCUSSION

Antimicrobial Metal-Ion Chemistry of Copper and Silver Vessels

Ayurvedic practice recommends storing drinking water overnight in copper vessels. Controlled microbiological testing confirms this practice eliminates diarrhoeagenic bacteria within sixteen hours, while copper concentrations in the treated water remain within permissible limits.[1]

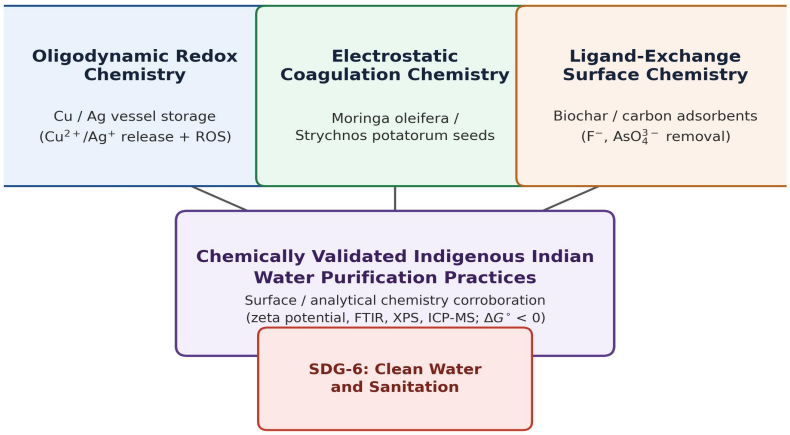

Fig.-1: Schematic Overview of the Three Principal Chemical-Mechanism Classes Underlying the Indigenous Water Purification Practices Reviewed, and their Collective Alignment with SDG-6 (Clean Water and Sanitation). This Conceptual Summary is Distinct From, and does not Duplicate, the Mechanism-Level Detail Tabulated in Table-1.

The chemical basis is oxidative dissolution of metallic copper at the metal-water interface, releasing Cu^{2+} into solution (Eqn.-1), followed by Fenton-type generation of hydroxyl radicals that damage bacterial membrane proteins and DNA (Eqn.-2).

$$Cu(s) \rightarrow Cu^{2+}(aq) + 2e^{-} \quad (1)$$

$$Cu^{+} + H_2O_2 \rightarrow Cu^{2+} + OH^{\cdot} + OH^{-} \quad (2)$$

The same redox-driven principle underlies green-synthesised silver nanoparticles prepared from panchakavya, a traditional Indian agricultural formulation. Characterisation by UV-visible spectroscopy, transmission electron microscopy and X-ray diffraction confirms nanoscale, protein-capped silver formation, and the resulting nanoparticles exhibit concentration-dependent antibacterial activity through the same Ag^{+} release and reactive-oxygen-species mechanism.[2,3]

Coagulation Chemistry of Plant-Derived Seed Proteins

Turbidity removal by plant-seed coagulation is among the oldest documented Indian water-clarification practices.[4] *Moringa oleifera* seed contains water-soluble cationic proteins that adsorb onto the negatively charged surface of colloidal turbidity particles, neutralising surface charge and compressing the electrical double layer; once the resulting electrostatic energy barrier falls below the particles' thermal kinetic energy, van der Waals attraction dominates and the particles aggregate and settle.[5,6,9] In dairy-wastewater trials, *Moringa oleifera* seed achieved turbidity removal of up to 98% at low dosing, with performance approaching that of alum while generating substantially less chemical sludge.[5] A second, historically prominent Indian coagulant, the seed of *Strychnos potatorum* (nirmali), functions through an analogous charge-neutralisation mechanism mediated by anionic polysaccharide and protein fractions bearing carboxyl and hydroxyl functional groups; the same seed fractions additionally bind cadmium and achieve measurable fluoride removal, extending its role from simple clarification to a genuine multi-contaminant coagulant chemistry.[7] Zeta-potential analysis of *Moringa oleifera* seed extracts demonstrated that the coagulant increased the zeta potential of suspended particles, thereby reducing electrostatic repulsion and enhancing coagulation efficiency.[8]

Ligand-Exchange Chemistry of Fluoride Removal

Fluorosis remains a major geogenic groundwater hazard across large parts of India, and several indigenous or locally improvised adsorbents achieve defluoridation through ligand-exchange chemistry at hydroxylated metal-oxide or carbon surfaces. Surface hydroxyl groups (S-OH) exchange with aqueous fluoride ions, forming an inner-sphere surface complex and releasing hydroxide (Eqn.-3).

$$S{-}OH + F^{-} \rightleftharpoons S{-}F + OH^{-} \quad (3)$$

Functionalised carbon recovered as a by-product of *Musa balbisiana* (banana) stem processing adsorbs both fluoride (73% removal) and arsenate (nearly 80% removal) from spiked groundwater, demonstrating that a long-standing culinary waste-valorisation practice yields a genuinely functional defluoridation adsorbent.[10] This ligand-exchange chemistry is well-precedented in the broader fluoride-removal literature, which confirms that F^{-} competes with other oxyanions such as phosphate and silicate for the same surface sites, explaining the pH and matrix-sensitivity of field performance.[11,12] Critical reviews of arsenic adsorbent chemistry confirm that carbon, iron-oxide and clay-based adsorbents, chemically continuous with the materials used in indigenous practice, remain among the most viable low-cost routes to arsenic remediation via the same inner-sphere surface complexation chemistry.[13,14]

Surface and Analytical Chemistry Validation

Beyond isolated case studies, the chemical mechanisms above are corroborated by surface-sensitive and speciation-resolved analytical techniques. Green synthesis of iron oxide nanoparticles from waste banana-peel extract, characterised by X-ray diffraction, field-emission scanning electron microscopy and X-ray photoelectron spectroscopy, confirms the α-Fe_2O_3 phase responsible for arsenate binding, demonstrating that indigenous plant waste can serve as feedstock for engineered adsorbent chemistry.[15] Because arsenic toxicity and adsorptive behaviour depend on oxidation state rather than total concentration, speciation-resolved methods such as liquid chromatography–inductively coupled plasma mass spectrometry are essential to interpret removal chemistry correctly; comparative validation confirms this technique as the

most reliable of the available speciation methods for arsenite and arsenate.[16] The thermodynamic spontaneity of these adsorption and biosorption reactions is conventionally confirmed via the standard Gibbs free energy of adsorption, calculated from the distribution coefficient K_D (Eqn.-4); negative $\Delta G°$ values reported across this literature confirm that the surface chemistry proceeds spontaneously under ambient field conditions.[17,18]

$$\Delta G^\circ = -RT \ln K_D \quad (4)$$

Table-1 Consolidates the Chemical Mechanism, Governing Reaction, and Supporting Evidence for Each Indigenous Practice Reviewed Above

Table-1: Chemical Mechanisms Underlying Indigenous Indian Water Purification Practices

Practice	Chemical Mechanism	Governing Reaction	Ref.
Cu / Ag vessel storage	Oligodynamic ion toxicity; Fenton-type ROS generation	Eqs.-1, 2	1-3
Moringa oleifera seed coagulation	Electrostatic charge neutralisation of colloids	DLVO theory	4-6,9
Strychnos potatorum seed coagulation	Charge neutralisation; ligand exchange (F^-, Cd^{2+})	—	7
Banana-stem carbon adsorbent	Ligand exchange at hydroxylated surfaces	Eq.-3	10-14
Iron-oxide / magnetite adsorbents	Inner-sphere surface complexation (arsenate)	—	13-16
General adsorption/biosorption	Spontaneous reaction ($\Delta G° < 0$)	Eq.-4	17,18

Taken together, the findings summarised in Table-1 show that these indigenous practices are not isolated folk curiosities but converge on three well-precedented classes of chemistry - metal-ion redox/oligodynamic action, electrostatic coagulation, and ligand-exchange surface complexation - each independently corroborated by modern analytical techniques. This contributes to the field by reframing indigenous water treatment as an evidence-based chemical technology rather than an unexamined cultural practice, offering a mechanistic rationale that can guide the rational optimisation (dose, contact time, competing-ion tolerance) of these methods for real-world deployment. This chemical evidence base is directly substantiated against Sustainable Development Goal 6 (Clean Water and Sanitation): the oligodynamic, coagulation and ligand-exchange chemistries reviewed here collectively address microbial contamination, turbidity and geogenic fluoride/arsenic pollution, the principal barriers to SDG Target 6.1 (universal, equitable access to safe and affordable drinking water) in rural and semi-urban India.

CONCLUSION

This focused review of the chemical mechanisms of indigenous Indian water purification practices demonstrates that copper- and silver-vessel storage, plant-seed coagulation, and carbon-based defluoridation each rest on genuine, well-characterised chemistry: oligodynamic metal-ion redox chemistry, electrostatic protein-mediated coagulation, and ligand-exchange surface complexation, respectively. Surface-sensitive and speciation-resolved analytical techniques corroborate these mechanisms at the molecular level, and thermodynamic analysis confirms their spontaneity under field conditions. This chemistry-only synthesis offers a concise, scientifically defensible foundation on which future work can build standardised, low-cost water treatment systems for rural India. For practical translation, we recommend that future work (i) standardise dosing and contact-time protocols for Moringa oleifera, Strychnos potatorum and biochar-based adsorbents across variable field water matrices, (ii) validate long-term microbial and adsorptive performance, including regeneration and competing-ion effects, and (iii) integrate these chemistries into low-cost, community-scale purification kits. By strengthening the chemical evidence base for these practices, this review directly supports the achievement of Sustainable Development Goal-6 (Clean Water and Sanitation), particularly Target 6.1 on universal access to safe and affordable drinking water.

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CONFLICT OF INTERESTS

The authors declare that there is no conflict of interest.

AUTHOR CONTRIBUTIONS

The present work is related to *SDG-6: Clean Water and Sanitation*. All the authors contributed significantly to this manuscript, participated in reviewing/editing and approved the final draft for publication. The research profile of the authors can be verified from their ORCID ids, given below:

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