

Comprehensive Analysis for Removal of Contamination in Groundwater by Brick Powder

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Abstract: Groundwater contamination by fluoride, heavy metals, arsenic, and other inorganic pollutants remains a significant public health challenge in many developing regions, where groundwater is often the primary source of drinking water. Conventional treatment technologies such as reverse osmosis, ion exchange, and membrane filtration are effective but frequently too costly, energy-intensive, or technically demanding for decentralized or rural application. This has driven sustained interest in low-cost, locally available adsorbents, among which waste brick powder — derived from discarded or broken fired clay bricks, cement bricks, and construction and demolition (C&D) debris — has emerged as a promising material. This review synthesizes findings from studies published between 2021 and 2024 on the use of brick powder and related brick-derived materials (brick sand nanoparticles, cement brick waste, aerated concrete/clay brick blends, and metal-modified brick powder) for the removal of fluoride, heavy metals (lead, cadmium, chromium, copper, nickel, iron), and other contaminants from groundwater and aqueous solution. The mechanisms of adsorption, the influence of operating parameters (pH, contact time, adsorbent dose, particle size, and temperature), isotherm and kinetic modelling, comparative performance against other low-cost adsorbents, and the circular-economy rationale of reusing construction waste are discussed. The review concludes that brick powder is a technically viable, economically attractive, and environmentally sustainable adsorbent for point-of-use and community-scale groundwater treatment, though its moderate adsorption capacity relative to engineered adsorbents indicates a need for surface modification (acid activation, iron/metal impregnation) to enhance performance for field deployment.

Keywords: brick powder; groundwater contamination; adsorption; fluoride removal; heavy metal removal; low-cost adsorbent; construction and demolition waste; water treatment

1. Introduction

Groundwater serves as the principal source of drinking water for more than two billion people worldwide, particularly in rural and semi-arid regions where surface water is scarce or seasonally unreliable. However, groundwater quality is increasingly compromised by both geogenic contamination (fluoride, arsenic, iron) and anthropogenic pollution (heavy metals, nitrates, industrial effluents), posing serious risks to human health, including skeletal and dental fluorosis, arsenicosis, and heavy-metal toxicity. Millions of people, especially in South Asia, Sub-Saharan Africa, and parts of Latin America, rely on groundwater sources that exceed World Health Organization (WHO) guideline values for one or more of these contaminants.

Conventional remediation techniques — including coagulation-precipitation, ion exchange, reverse osmosis, electrodialysis, and membrane filtration — are technically effective but often unsuitable for low-income or rural settings because of high capital and operating costs, dependence on electricity, and the need for skilled operation and maintenance. Adsorption has consistently been identified as one of the most practical alternatives because it is simple to operate, does not generate secondary sludge in large volumes, can be implemented at household or community scale, and allows the use of inexpensive, locally sourced materials as adsorbents.

Among the wide range of low-cost adsorbents investigated over the past decade — including agricultural residues, biochar, fly ash, and natural clays — waste brick powder has attracted growing attention. Bricks are ubiquitous

construction materials, and broken or rejected bricks (from kilns, demolition sites, and construction waste) represent an abundant, virtually cost-free raw material. Fired clay bricks are composed predominantly of silica, alumina, and iron oxides, with a porous structure that develops during kiln firing; this composition and porosity confer surface reactivity and physical adsorption capacity for a range of aqueous contaminants. Using such waste as an adsorbent additionally supports circular-economy objectives by diverting construction and demolition (C&D) waste from landfill while providing an affordable water-treatment option for underserved communities.

This review focuses specifically on peer-reviewed research published between 2021 and 2024 examining the use of brick powder and related brick-derived materials for the removal of contaminants from groundwater and aqueous solutions. It covers the physicochemical basis of adsorption on brick powder, its performance against major groundwater contaminants (fluoride, heavy metals, and arsenic-associated iron), the operational parameters governing removal efficiency, comparative performance relative to other low-cost adsorbents, and outstanding research gaps.

2. Groundwater Contamination: Sources, Distribution, and Health Significance

Fluoride contamination is one of the most widespread geogenic groundwater problems, with more than 200 million people estimated to depend on groundwater exceeding the WHO guideline of 1.5 mg/L, arising primarily from the weathering of fluoride-bearing minerals such as fluorite and apatite in aquifer rocks. Chronic ingestion of excess fluoride causes irreversible dental and skeletal fluorosis, particularly in parts of India, China, East Africa, and parts of Latin America.

Arsenic contamination of groundwater affects an estimated 170 million or more people globally, and is especially severe in the alluvial and deltaic aquifers of Bangladesh, India, China, Cambodia, and Vietnam, where reducing aquifer conditions mobilize naturally occurring arsenic from sediments. Long-term exposure is associated with arsenicosis, skin lesions, and increased cancer risk, making cost-effective removal technologies for rural point-of-use application a persistent priority.

Heavy-metal contamination of groundwater (lead, cadmium, chromium, copper, nickel, and iron) is typically anthropogenic, resulting from industrial effluent discharge, mining activity, improper disposal of electronic and metallurgical waste, and infiltration from contaminated surface water or soil. Heavy metals are non-biodegradable and bioaccumulative, and even trace concentrations can cause neurological, renal, and carcinogenic effects with prolonged exposure. Because heavy metals resist conventional biological treatment, physicochemical methods such as adsorption remain the most reliable pathway for their removal from contaminated water.

3. Bricks and Brick Powder as an Adsorbent Material

Fired clay bricks are manufactured by moulding a mixture of clay, sand, and sometimes additives, followed by firing at temperatures typically between 900 °C and 1100 °C. This thermal treatment converts the clay minerals into a matrix rich in quartz, mullite, and amorphous or crystalline aluminosilicate and iron-oxide phases, while generating internal micro- and meso-porosity. When bricks are crushed and ground into powder, this porous, mineral-rich matrix presents a relatively high surface area with numerous hydroxyl and metal-oxide functional groups capable of interacting with dissolved ions through physical adsorption, surface complexation, ion exchange, and electrostatic attraction.

Several categories of brick-derived adsorbents have been investigated in the recent literature: (i) plain waste brick powder obtained by washing, drying, and sieving crushed kiln rejects or demolition bricks; (ii) brick sand nanoparticles (BSNP) produced by fine milling to nanometre-scale particle size to increase surface area; (iii) cement brick waste (CBW) and aerated-concrete/clay-brick blends from construction and demolition debris; and (iv) chemically or metal-modified brick powder (e.g., acid-activated, iron-coated, or lanthanum/iron bimetallic-modified brick powder) designed to enhance selectivity and capacity for specific contaminants such as fluoride,

arsenic, or phosphate. Across these variants, the shared advantages are negligible material cost, wide availability (bricks are produced and discarded in enormous volumes worldwide), simple preparation (crushing, washing, drying, sieving), and compatibility with both batch (stirred-tank) and fixed-bed column configurations suitable for household or community filters.

4. Mechanisms and Modelling of Contaminant Adsorption on Brick Powder

Batch adsorption studies on brick-derived materials consistently report that the removal process is governed by a combination of physical adsorption onto porous surfaces, chemisorption via surface hydroxyl and metal-oxide groups, and, for cationic metals, ion exchange with structural cations (e.g., Ca, Na, K) present in the brick matrix. Karim et al. (2024) demonstrated that adsorption of Pb(II), Cd(II), and Cr(VI) onto brick sand nanoparticles followed pseudo-second-order kinetics, indicating that chemisorption is the rate-limiting step, and that the equilibrium data fitted multiple isotherm models (Langmuir, Freundlich, Temkin, Hill–de Boer, Elovich, and Redlich–Peterson), reflecting a heterogeneous, multilayer adsorption surface with both monolayer and cooperative adsorption behaviour. Thermodynamic analysis in the same study (activation energy, Gibbs free energy, enthalpy, and entropy changes) confirmed that the process was both feasible and favoured at moderately elevated temperatures (40–60 °C).

Similarly, Mokokwe and Letshwenyo (2022a, b) reported that the adsorption of Cu(II), Ni(II), and Fe(II) onto cement/clay brick waste was best described by the Freundlich isotherm with pseudo-second-order kinetics, and that column (fixed-bed) breakthrough behaviour followed the Yoon–Nelson model, supporting the feasibility of scaling brick-powder adsorption from batch to continuous-flow filtration systems. The point of zero charge (pH_{zpc}) of the cement brick waste was found to be approximately 8.8, meaning the adsorbent surface carries a net negative charge at typical groundwater pH values, favouring electrostatic attraction of cationic heavy metals.

For anionic contaminants such as fluoride, adsorption on unmodified brick powder is comparatively weaker because the negatively charged brick surface at near-neutral pH tends to repel fluoride ions; consequently, defluoridation studies report more modest removal efficiencies (typically 30–66%) compared with cationic heavy-metal removal, and performance improves markedly with metal-oxide modification (e.g., iron or aluminium coating) that introduces positively charged surface sites for anion exchange.

5. Performance of Brick Powder Against Specific Groundwater Contaminants

5.1 Heavy Metals (Pb, Cd, Cr, Cu, Ni, Fe)

The removal of heavy metals is the most extensively documented application of brick-derived adsorbents in the 2021–2024 literature. Karim et al. (2024) reported that acid-treated and untreated brick sand nanoparticles (mean particle size 44.2 nm) achieved 97% removal of Pb(II), Cd(II), and Cr(VI) at pH 5.68–7.6, rising to 98% at elevated temperature, positioning brick sand nanoparticles as a highly competitive low-cost nanoadsorbent. Mokokwe and Letshwenyo (2022a, b) showed that waste clay/cement brick powder effectively removed Cu(II), Ni(II), and Fe(II) from aqueous solution in both batch and fixed-bed column modes, with satisfactory reusability across at least two adsorption–desorption cycles, indicating practical durability for repeated field use. Yuan et al. (2023) compared powdered clay bricks with aerated concrete derived from construction and demolition waste for Pb(II) removal, finding that aerated concrete achieved a markedly higher adsorption capacity (201.6 mg/g) than clay brick powder (56.3 mg/g), attributable to its higher porosity (~68% versus ~40% for clay brick), while both materials followed Langmuir and Freundlich isotherm behaviour.

5.2 Fluoride

Batch studies on the use of waste brick powder for defluoridation of groundwater report removal efficiencies in the range of roughly 30% to 66%, with optimum performance typically observed at pH 6.0–8.0, an adsorbent dose in the low g/L range, and an equilibrium contact time of approximately 120 minutes; determined adsorption

capacities for plain brick powder are modest (on the order of 1.5 mg/g), reflecting the relatively weak affinity of the unmodified aluminosilicate surface for the fluoride anion. Comparative work has shown that commercially available activated charcoal generally outperforms plain brick powder for defluoridation under equivalent conditions, but brick powder remains attractive because of its near-zero cost and local availability. To overcome the intrinsic limitations of unmodified brick powder, researchers have combined it with other low-cost materials — for example, fusing brick powder with alum and calcium chloride, or coating it with iron or aluminium compounds — to substantially enhance fluoride uptake by introducing positively charged adsorption sites that favour anion exchange.

5.3 Arsenic and Associated Iron Removal

Arsenic removal using brick-derived media is most commonly implemented through iron-coated brick chips rather than fine brick powder, reflecting the need for adequate hydraulic conductivity in gravity-fed household filters. Household filter designs such as the iron-coated brick chip (“Shapla”) filter, and composite filters combining zero-valent iron, sand, brick chips, and wood coke (e.g., SONO, Kanchan™, and SAFI-type filters), have been widely deployed and studied across South and Southeast Asian countries where arsenic-affected aquifers threaten drinking-water supplies (Shaji et al., 2021). The iron coating provides reactive hydrous iron-oxide surface sites (ferrihydrite-like OH_2^+ , OH^- , and O^- groups) that bind both As(III) and As(V) via ligand exchange and surface complexation, while the coarser brick-chip substrate maintains sufficient porosity for continuous gravity flow, illustrating a design trade-off between fine brick powder (higher surface area, lower hydraulic conductivity) and coarser brick chips (lower surface area, higher hydraulic conductivity) depending on the intended filter configuration.

5.4 Organic Pollutants and Dyes

Compared with heavy-metal and fluoride removal, direct application of brick powder to the adsorption of organic pollutants and synthetic dyes remains comparatively underexplored in the reviewed literature; most dye-adsorption research from 2021–2024 has focused on biomass-derived, mineral, and industrial by-product adsorbents such as biochar, red mud, fly ash, and modified clays, which share a similar low-cost rationale with brick powder. Given that brick powder and other cementitious construction wastes have shown adsorption capability for other anionic and cationic species, extension of brick-powder-based adsorption to textile dyes and other organic micropollutants represents a plausible but still largely untested research direction, and is identified below as a gap for future study.

6. Factors Influencing Adsorption Performance

Across the reviewed studies, five operating parameters consistently govern the efficiency of contaminant removal by brick-derived adsorbents:

- **Solution pH:** Controls the surface charge of the brick matrix and the speciation of the target contaminant; cationic heavy-metal removal is generally favoured at near-neutral to mildly alkaline pH (5–8), whereas anionic fluoride removal is comparatively favoured at slightly acidic to neutral pH before declining at higher alkalinity due to competition with hydroxide ions.
- **Contact time:** Most studies report equilibrium being reached within 60–120 minutes, with rapid initial uptake in the first 15–30 minutes followed by a slower approach to saturation as available surface sites are progressively occupied.
- **Adsorbent dose:** Removal efficiency generally increases with adsorbent dose up to an optimum, beyond which further dose increases yield diminishing returns due to particle aggregation and reduced effective surface area per unit mass.

- Particle size and surface area: Finer particle sizes (e.g., nanoscale brick sand particles) provide substantially greater surface area and consistently outperform coarser brick chips in batch capacity, although coarser materials retain advantages for hydraulic conductivity in continuous-flow filters.
- Temperature: Several studies report improved removal at elevated temperature (up to 40–60 °C), consistent with an endothermic, chemisorption-dominated process, although ambient-temperature performance remains adequate for most practical field applications.

Table 1. Summary of Reviewed Studies

Contaminant	Brick-based adsorbent	Removal efficiency	Adsorption capacity / conditions	Reference
Pb(II), Cd(II), Cr(VI)	Brick sand nanoparticles (BSNP, ~44 nm), acid-treated & untreated	Up to 97–98%	Optimum pH 5.68–7.6; 40–60 °C; pseudo-second-order kinetics; Langmuir/Freundlich/Temkin fits	Karim et al. (2024)
Cu(II), Ni(II), Fe(II)	Waste clay/cement brick powder (Makoro granite brick)	High removal in batch & column modes	pH _{zpc} 8.8; Freundlich isotherm; pseudo-second-order kinetics; reusable for 2 cycles	Mokokwe & Letshwenyo (2022a, b)
Pb(II)	Powdered clay bricks (CB) and aerated concrete (AC) from C&D waste	CB: up to 56.3 mg/g; AC: 99.0% removal	Optimum pH 5.0; contact time 1 h; dosage 5 g/L; Langmuir & Freundlich models	Yuan et al. (2023)
Fluoride (F ⁻)	Waste brick powder (<300 µm)	Up to 66%	Optimum pH 6.0–8.0; equilibrium time ~120 min; capacity 1.46 mg/g	Brick-powder defluoridation batch study (2023), Trans. Nonferrous Met. Soc. China
Arsenic (As III/V)	Iron-coated brick chips (household filters, e.g., “Shapla” filter)	Substantial As(III) and As(V) removal in field filters	Ferrous sulphate coating; gravity-fed household units used across South & Southeast Asia	Reviewed in Shaji et al. (2021)

7. Advantages, Limitations, and Sustainability Considerations

7.1 Advantages

- Extremely low material cost, as feedstock is waste or reject brick otherwise destined for landfill.

- Simple preparation requiring only crushing, washing, drying, and sieving — no specialised chemical synthesis.
- Compatibility with both batch treatment and fixed-bed/column filter configurations for household or community use.
- Demonstrated reusability over multiple adsorption cycles in column studies, supporting operational durability.
- Alignment with circular-economy and construction-and-demolition (C&D) waste-management objectives, converting an environmental liability into a water-treatment resource.

7.2 Limitations

- Adsorption capacities of unmodified brick powder are generally lower than engineered or chemically modified adsorbents (e.g., activated carbon, metal-oxide nanocomposites), particularly for anionic species such as fluoride.
- Performance is sensitive to competing ions and background water chemistry present in real groundwater, which can reduce removal efficiency relative to idealized synthetic solutions.
- Most published studies remain at laboratory batch or small-column scale; field-scale, long-term performance data under variable groundwater conditions are still limited.
- Fine brick powder has low hydraulic conductivity, restricting its direct use in gravity-fed filters without blending with coarser media.

8.3 Circular-Economy and Waste-Management Synergies

An emerging complementary strand of research examines the reverse pathway — safely incorporating spent (contaminant-loaded) adsorbents, including biomass-derived materials, back into fired clay bricks as pore-forming or structural additives, thereby closing the material loop between water treatment and construction. Such approaches demonstrate that the interaction between bricks and adsorption processes extends beyond using brick waste as an adsorbent, toward an integrated circular system in which spent water-treatment media are safely stabilized within construction materials, reducing the net environmental footprint of both industries.

8. Research Gaps and Future Directions

- Field validation: Most studies rely on synthetic contaminant solutions; more field trials using real, multi-contaminant groundwater are needed to confirm performance under representative conditions.
- Surface modification: Systematic comparison of modification strategies (acid activation, iron/aluminium coating, bimetallic loading) is needed to establish which approaches offer the best cost-to-performance ratio for fluoride and arsenic removal specifically.
- Column and pilot-scale studies: Fixed-bed breakthrough behaviour, regeneration cycles, and long-term media life under continuous flow require further investigation beyond the limited column studies currently available.
- Life-cycle and leaching assessment: Comprehensive life-cycle assessment and leachate testing (to confirm that spent brick-powder adsorbents do not themselves release contaminants) remain underreported.
- Dye and organic micropollutant removal: Brick-powder adsorption of synthetic dyes, pharmaceuticals, and other emerging organic contaminants is largely unexplored relative to heavy metals and fluoride.

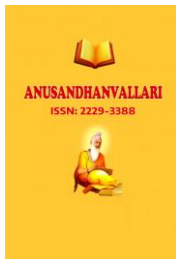
- Standardization: Variability in brick source material (fired clay, cement brick, aerated concrete) and preparation method makes cross-study comparison difficult; standardized characterization and reporting protocols would strengthen the evidence base.

9. Conclusion

The literature published between 2021 and 2024 provides consistent evidence that waste brick powder and related brick-derived materials — including brick sand nanoparticles, cement/clay brick waste, and aerated-concrete blends from construction and demolition debris — are technically effective, low-cost adsorbents for removing heavy metals, fluoride, and, in coated form, arsenic from groundwater and aqueous solutions. Removal efficiencies exceeding 95% have been reported for cationic heavy metals such as Pb(II), Cd(II), and Cr(VI) under optimized batch conditions, while fluoride removal by unmodified brick powder is more modest (30–66%) but can be substantially improved through metal-oxide surface modification. The combination of negligible cost, wide availability, simple preparation, and compatibility with decentralized filtration systems makes brick powder a practical option for community and household-scale groundwater treatment in resource-constrained settings, while simultaneously advancing circular-economy goals by valorising construction and demolition waste. Continued research into surface modification, field-scale validation, and standardized testing protocols will be essential to move brick-powder-based adsorption from promising laboratory results toward widespread, reliable field deployment.

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