

Review Article

Toxicological Impact of Heavy Metals During Sustainable Brick Production from Bagasse and Fly Ash: A Review

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Abstract

The utilization of waste materials in the construction technology is today considered an important key to meet sustainability level goals and reduce carbon dioxide emissions through a minimum use of virgin production chains. Coal fly ash (CFA) and sugarcane bagasse ash (SBA) are the two types of waste byproducts for which there has been promising reuse in a sustainable brick. Both ashes are characterized by their high contents of silica and alumina that makes them of potential interest as partial substitutes for clay in fired bricks or as precursors in geopolymerization. But the trace amount of heavy metals such as arsenic, cadmium, chromium, lead, mercury, nickel and zinc in the materials may cause some toxicological threat to human health and ecosystem if it is not well immobilized during its fabrication as well as usage. This review summarises information on the chemical composition of CFA-, and SBA-brick constituents, i.e. raw materials used in bricks including those substituting conventional brick materials, methods by which heavy metals are sequestered in bricks, toxicological pathways following exposure to leachates from such bricks and leaching regulations and risk assessment specifications globally. It also presents the mitigation approaches to minimize metal toxicity, discusses analytical difficulties and finally outlines future research perspective necessary to elevate safe and sustainable ash masonry use.

Keywords

Coal Fly Ash, Sugarcane Bagasse, Analytical Characterization, Soil, Cement

1. Introduction

The international construction industry is increasingly being pressured to be more sustainable as the issues of resource depletion, waste generation and climate change become more prominent. There is great amount of energy consumed and damage to the environment in mining clay and high-temperature firing, which are used in traditional brick production. To this end, researchers and industries have sought new raw materials that can be locally sourced in large quantity and are environmentally benign [1]. However, coal fly ash and sugarcane bagasse ash are notable in this case as

they are waste products from thermal power plants and sugar/ethanol industries respectively emerging as additional source of raw material for the brick production.

Coal fly ash [2] is globally being produced in massive amounts and India alone produces over 226 million tonnes annually. If not well handled, dumping of CFA could result in land use competition, dust pollution, ground water degradation and ecological damage. However, the ash derived from the burning of sugarcane bagasse (SBA) is obtained as a fibrous waste produced after juice extraction. Due to India

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being one of the biggest sugar producing countries, SBA is an important source of agricultural waste with significant potential for recycling into construction materials [3].

Valorising of CFA and SBA for brick production has environmental advantages in terms of diversion from landfilling, saving natural clays and other previously exploited raw materials; however, toxicological fear concerning metalloids released into the air during combustion was still raised. Workers, residents and environment around manufacturing, using and demolishing ash-based bricks will be exposed to heavy metals. Therefore, it is crucial to understand the forms of metal release, their toxicological response and whether stabilization measures will be effective in order to safeguard the justice boss read online the safe reuse of CFA and SBA in sustainable construction.

1.1. Chemical Composition of Fly Ash and Bagasse

Coal fly ash (CFA) and sugarcane bagasse (SB) are both residues of combustion processes, but their mineralogy, chemical structure, and trace element contents differ considerably. Understanding their composition is essential for evaluating their pozzolanic reactivity, environmental safety, and toxicological implications in sustainable brick production.

1.2. Coal Fly Ash (CFA)

CFA is an ash formed by combustion of pulverized coal in thermal power plants. Its chemistry is characteristic of both the parent coal mineral matter and combustion temperature. The main oxides are silica (SiO_2 , 40-60%), alumina (Al_2O_3 , 20-30%) and iron oxide (Fe_2O_3 , 5-20%). Calcium oxide (CaO) has a wide range: <10% for Class F fly ash and 10-30% for Class C fly ash [4]. Trace oxides such as MgO , K_2O , Na_2O , and TiO_2 are also present. The smaller size (<45 μm), spherical shape and amorphous state of particles can improve the pozzolanic activity [5]. However, CFA also contains trace heavy metals such as arsenic (As), cadmium (Cd), chromium (Cr), lead (Pb), mercury (Hg), nickel (Ni) and selenium (Se) which is concentrated on particle surfaces with increased leaching possibility [6].

1.3. Sugarcane Bagasse (SB)

Output

SB is the product of sugarcane residue during combustion of bagasse following juice extraction in sugar factories. It is dominated by silica (50-80%) that could be crystalline or amorphous depending on the conditions of combustion [7]. Additional oxides are Al_2O_3 , Fe_2O_3 , and CaO but in general on a lesser level than CFA. The chemical composition of SB is extremely different because the properties of soil, the type and amount of fertilizers and pesticides used, and temperature

used for combustion. In contrast to CFA, SB often displays higher loss on ignition (LOI) values owing to incomplete burning resulting in unburnt carbon [8]. The content of heavy metals is generally lower than CFA, but site-specific contamination caused, in particular by agrochemicals at the end-of-life stage, which can increase Pb, Cd and Cr [9].

1.4. Analytical Characterization

Techniques such as X-ray fluorescence (XRF), inductively coupled plasma mass spectrometry (ICP-MS) and X-ray diffraction (XRD) are well known for assessing oxide content, trace metals of CFA and SB. These characterizations are important to predict reactivity in brick production and to evaluate the risks of leaching [10]. The high ratio of CFA and SB silica content indicates that both are pozzolanic materials, although the toxicological hazards associated with their use will be determined by feedstock variation, combustion conditions, and stabilization processes.

1.5. Pathways of Heavy Metal Exposure

The release and subsequent exposure of humans or the environment to heavy metals are the main toxicological risks connected to the use of coal fly ash (CFA) and sugarcane bagasse (SB) in the production of sustainable bricks. The way pollutants enter biological systems and affect their bioavailability and toxic effects is defined by exposure pathways. Inhalation, ingestion, skin contact, and indirect pathways through contaminated soil and water are the main exposure routes.

1.6. Inhalation Pathway

Heavy metal-containing fine particulate matter may be released into the air during the handling, mixing, and processing of CFA and SB in the brick-making process. Because they can get past the upper respiratory defenses and lodge deep in the lungs' alveolar regions, particles smaller than 10 μm (PM10) or ultrafine fractions (<2.5 μm) are especially dangerous. Pulmonary inflammation, oxidative stress, and carcinogenic consequences have been linked to inhaling airborne particles enriched with metals like Cr, Pb, As, and Cd [11]. Workers in manufacturing facilities and brick kilns where dust suppression measures are inadequate are particularly vulnerable to occupational exposure.

1.7. Ingestion Pathway

When exposed to acidic environments, rainwater, or landfill leachate following demolition, heavy metals that have been immobilized within bricks may leak out. Through agricultural products irrigated with tainted water, these pollutants can enter the food chain by penetrating soil and groundwater systems. Chronic exposure to trace metals like arsenic, lead,

and cadmium has been associated with carcinogenesis, nephrotoxicity, and gastrointestinal problems [12]. In workplace settings, ingestion can also happen indirectly through hand-to-mouth behavior, especially when safety procedures are not properly followed.

1.8. Dermal Contact

For workers who handle ash or unfinished bricks directly, dermal absorption becomes important even though it is a less important pathway than ingestion or inhalation. Long-term exposure to metals that are known to cause skin sensitization, such as nickel and chromium, can result in systemic absorption or allergic contact dermatitis [13]. With the right safety gear, this pathway is usually reduced, but it can still be dangerous in unlicensed or small-scale brick manufacturing facilities.

1.9. Soil and Water Contamination

Groundwater and nearby soil can become contaminated by heavy metals that leach from weathered or discarded bricks. Metals may bioaccumulate and biomagnify through food webs once they are in the environment. For example, through dietary intake, lead and cadmium absorbed by plants can eventually reach animals and humans [14]. Communities that live close to brick manufacturing or disposal sites should be especially concerned about this indirect exposure pathway because long-term ecological accumulation can make health risks worse.

1.10. Toxicological Effects of Heavy Metals

One of the main concerns when assessing the safe use of coal fly ash (CFA) and sugarcane bagasse (SB) in sustainable brick production is the toxicological impact of the heavy metals present in these materials. According to Jaishankar et al. (2014), heavy metals like arsenic (As), cadmium (Cd), lead (Pb), chromium (Cr), mercury (Hg), and nickel (Ni) are non-biodegradable and have a tendency to bioaccumulate in human tissues. Depending on the dose, length of exposure, and biological susceptibility of the exposed population, these metals can cause a variety of harmful health effects. These metals can enter the body through the skin, contaminated food or water, or dust inhaled during manufacturing.

1.10.1. Arsenic (As)

Arsenic is often present in CFA and can leach into groundwater under alkaline or reducing conditions. Chronic arsenic exposure is associated with skin lesions, hyperkeratosis, and an increased risk of cancers of the skin, lung, and bladder [15]. Inhalation of arsenic-contaminated particulates also contributes to respiratory distress and immune suppression.

1.10.2. Cadmium (Cd)

Cadmium occurs in trace amounts in both CFA and SB,

particularly in areas with agricultural contamination. Once absorbed, cadmium accumulates in the kidneys and liver, causing nephrotoxicity, skeletal damage, and cardiovascular complications [16]. Long-term cadmium exposure is also linked to reproductive toxicity and carcinogenicity.

1.10.3. Lead (Pb)

Lead is one of the most critical toxicants due to its impact on neurological development. In children, even low levels of lead exposure can cause cognitive impairment, learning disabilities, and behavioral disorders [25]. In adults, lead exposure contributes to hypertension, renal dysfunction, and reproductive disorders. Bricks containing leachable Pb pose a direct threat when used in housing environments.

1.10.4. Chromium (Cr)

Chromium exists in multiple oxidation states, with hexavalent chromium (Cr(VI)) being the most toxic. Cr(VI) is highly soluble and can cause oxidative stress, DNA damage, and carcinogenesis [27]. Occupational exposure through inhalation of chromium-laden dust during brick production may lead to respiratory diseases, including asthma and lung cancer.

1.10.5. Mercury (Hg)

Mercury is volatile and can bioaccumulate in the food chain. Although present in relatively low concentrations in CFA, mercury poses neurological risks, particularly in fetuses and young children [17]. Chronic mercury exposure has also been associated with tremors, memory loss, and cardiovascular disease.

1.10.6. Nickel (Ni)

Nickel exposure, often from CFA, is associated with allergic reactions, respiratory disorders, and carcinogenic effects. Prolonged inhalation of nickel compounds is linked with lung fibrosis and cancers of the nasal cavity and lungs [18].

When taken as a whole, these toxicological hazards highlight how crucial it is to assess the bioavailability and leachability of heavy metals in bricks manufactured using CFA and SB. Bricks released to the market are protected from contributing to hazardous exposures by regulatory frameworks that frequently set threshold limits for heavy metals in leachates (e.g., EPA Toxicity Characteristic Leaching Procedure; EU Waste Acceptance Criteria) [19]. To protect public health, however, long-term monitoring of exposure pathways is required, especially in low-income communities where such bricks may be used.

2. Leaching Behavior and Metal Immobilization Mechanisms

One important factor influencing the environmental safety and toxicological effects of bricks made from coal fly ash

(CFA) and sugarcane bagasse (SB) is how heavy metals leach from them. While immobilization mechanisms explain the physical and chemical processes that limit such release, leaching refers to the release of soluble contaminants when materials come into contact with water. Predicting the long-term stability of heavy metals in sustainable brick matrices requires an understanding of both processes.

2.1. Leaching Behavior of Heavy Metals

The structural integrity of the brick matrix, mineralogy, redox potential, and pH all have a significant impact on the mobility of heavy metals from CFA and SB. As an example, cadmium (Cd), lead (Pb), and zinc (Zn) exhibit higher solubility in acidic environments, whereas arsenic (As), selenium (Se), and molybdenum (Mo) tend to leach more in alkaline conditions [20]. Leaching potential is frequently assessed using laboratory tests like the Synthetic Precipitation Leaching Procedure (SPLP), the Toxicity Characteristic Leaching Procedure (TCLP, US EPA Method 1311), and European standards like EN 12457 [21]. Bricks fired at high temperatures ($\geq 900^{\circ}\text{C}$) reduce leachability by changing heavy metals into stable crystalline or glassy phases, according to numerous studies [26].

Because Cr, Pb, and Ni are encapsulated in aluminosilicate matrices, CFA-based bricks typically exhibit lower leachability of these metals [22]. On the other hand, volatile elements like As and Hg may partially evaporate during firing, condensing in kiln cooler zones or redistributing into fine particles [1]. Because SB-based bricks have a higher silica content and form calcium-silicate-hydrate (C-S-H) gels that firmly bind trace metals, metal leaching is generally lower for these bricks [1]. However, localized risks of increased Pb and Cd release can be introduced by incomplete combustion and variations in feedstock quality [9].

2.2. Immobilization Mechanisms

The immobilization of heavy metals in ash-based bricks is governed by several interrelated mechanisms:

2.3. Physical Encapsulation

Heavy metals are trapped within the dense microstructure of fired bricks, reducing their exposure to leaching fluids. High firing temperatures promote vitrification, creating glassy phases that effectively seal metals [26].

2.4. Chemical Incorporation into Crystal Lattices

Metals such as Cr and Ni can substitute for Al or Si in aluminosilicate frameworks, while Pb and Cd may form stable spinel or ferrite phases during sintering [23].

2.5. Adsorption onto Mineral Surfaces

Amorphous silica, iron oxides, and alumina phases provide sorption sites that immobilize cations such as Pb^{2+} , Cd^{2+} , and Ni^{2+} [24].

2.6. Formation of Hydrated Phases

In blended systems with cementitious components, calcium-silicate-hydrate (C-S-H) gels can encapsulate or chemically bind trace metals, further reducing leachability [25].

2.7. Redox Transformations

The oxidation state of metals influences their solubility. For example, Cr(VI), highly mobile and toxic, can be reduced to the less soluble Cr(III) during high-temperature firing, thus decreasing environmental risk [26].

2.8. Environmental Relevance

Under controlled processing conditions, CFA- and SB-based bricks usually meet international leaching limits thanks to the combined action of these immobilization mechanisms [27]. However, the stability of immobilized metals can be impacted by variations in kiln operation, brick formulations, and ash feedstock. Therefore, to completely prove the safety of these sustainable materials, long-term leaching studies under simulated environmental conditions (acid rain, fluctuating pH, freeze-thaw cycles) are required.

3. Human Health Risk Assessments

The Human Health Risk Assessment (HHRA) is a crucial framework for assessing the possible negative health effects of exposure to heavy metals that are leached from materials used in the production of sustainable bricks, such as fly ash (FA) and sugarcane bagasse (SB). The evaluation offers a methodical approach to measuring exposure and forecasting health risks that are both carcinogenic and non-carcinogenic.

3.1. Framework of HHRA

Hazard identification, dose-response assessment, exposure assessment, and risk characterization are the four main phases of HHRA, according to the U.S. Environmental Protection Agency (USEPA) [28]. Identifying the types of heavy metals present in FA and SB-based bricks, such as arsenic (As), cadmium (Cd), chromium (Cr), mercury (Hg), nickel (Ni), and lead (Pb), is necessary for hazard identification. These metals are known to be hazardous even at low concentrations [29].

3.2. Exposure Pathways

Determining the potential routes of human exposure to heavy metals requires exposure assessment. Three main pathways predominate for bricks made of FA and SB: (i) ingestion of tainted groundwater from metal leaching, (ii) inhalation of dust from weathered or poorly cured bricks, and (iii) skin contact, particularly during handling and construction in occupational settings [26]. Compared to adults, children have higher health risk indices and are more susceptible to exposure through hand-to-mouth ingestion [30].

3.3. Risk Characterization

The Hazard Quotient (HQ) and Hazard Index (HI), which contrast estimated daily intake (EDI) with reference doses (RfD), are commonly used to express non-carcinogenic risks. Potential health issues are indicated by HQ or HI values greater than unity ($HQ > 1$) [31]. Lifetime Cancer Risk (LCR), which is calculated from exposure concentrations and slope factors for carcinogens like As, Cr(VI), and Cd, is a measure of carcinogenic risks [19]. As and Cr(VI) are frequently found to be the main causes of carcinogenic risks in FA-based materials, while Pb and Hg have a greater impact on non-carcinogenic results [32].

3.4. Cumulative and Synergistic Effects

HHRA's consideration of cumulative and synergistic effects is another crucial component. Metals are rarely found alone, and exposure to multiple metals can increase toxicity. For example, co-exposure to Pb and Cd has been associated with more neurotoxic effects than exposure to either metal alone [33]. This calls for integrated risk assessment methods that take into consideration a variety of contaminants.

3.5. Application in Sustainable Brick Production

HHRA has been used in recent research to evaluate the safety of bricks composed of FA and SB. Results indicate that metal bioavailable fractions can be decreased by immobilization processes like pozzolanic reactions, which lowers overall risk indices [34]. Long-term leaching under fluctuating pH and temperature conditions is still an issue, though, particularly in areas with a high reliance on groundwater. Therefore, risk assessments are a crucial instrument for establishing regulatory boundaries, enhancing stabilization methods, and guaranteeing public health and safety when using sustainable building materials.

4. Regulatory Frameworks

To protect the environment and public health, heavy metal emissions and leaching from industrial byproducts like sugarcane bagasse (SB) and coal fly ash (CFA) must be con-

trolled. Regulatory frameworks offer uniform standards to control waste classification, set safe disposal or reuse procedures for building materials like sustainable bricks, and restrict allowable levels of hazardous metals.

4.1. International Standards

Global threshold limits for heavy metals in soil, water, and air are established by agencies like the European Union (EU) and the World Health Organization (WHO). Maximum contaminant levels (MCLs) for arsenic (10 $\mu\text{g/L}$), cadmium (3 $\mu\text{g/L}$), and lead (10 $\mu\text{g/L}$) are among those specified in WHO drinking water quality guidelines [35]. Coal combustion products are categorized by the EU Waste Framework Directive (2008/98/EC), which also requires leachability testing prior to reuse in construction. Leaching limit values for heavy metals like As, Cr, and Pb are emphasized in the EU Council Decision 2003/33/EC, which also establishes criteria for waste acceptance at landfills [36].

4.2. United States Regulations

Coal combustion residuals (CCRs) are governed by the Resource Conservation and Recovery Act (RCRA) of the Environmental Protection Agency (EPA) in the United States. Groundwater monitoring, liner systems, and fly ash impoundment closure are all outlined in the 2015 CCR Rule [37]. Additionally, the EPA establishes reference doses for heavy metal exposure used in Human Health Risk Assessments and enforces Maximum Contaminant Levels (MCLs) for drinking water [38]. By guaranteeing consistent quality, ASTM standards like ASTM C618 indirectly address safety by defining the chemical and physical requirements for using fly ash in cement and concrete [39].

4.3. Indian Context

One of the biggest producers of fly ash, India, has a clear policy framework for using it. Through a series of notifications, the Ministry of Environment, Forests, and Climate Change (MoEFCC) requires thermal power plants to use 100% fly ash, mainly for construction activities [40]. The Bureau of Indian Standards (BIS) establishes requirements for blended cement (IS 1489:1991) and fly ash-lime bricks (IS 12894:2002). There is a need for risk-based guidelines that are in line with global best practices, as India's regulatory framework prioritizes utilization over comprehensive leachability standards [41].

4.4. Gaps and Challenges

Even with regulatory frameworks in place, a number of issues still exist. First, bulk utilization is frequently the focus of regulatory attention rather than trace element mobility and toxicological hazards. For instance, heavy metal leaching

under a variety of environmental conditions (such as acid rainwater and fluctuating groundwater levels) is not adequately addressed, despite fly ash being widely promoted for sustainable construction [26]. Second, there is a lack of global standardization; different jurisdictions have different metal permissible limits, which makes international technology transfer and material trade challenging. Third, small-scale and informal brick kilns, particularly in developing nations, frequently evade regulatory enforcement, raising risks to community and occupational health [42].

4.5. Need for Risk-Based Standards

Regulatory frameworks must change to adopt risk-based strategies in order to guarantee the long-term adoption of bricks based on FA and SB. This includes (i) mandatory HHRA for newly developed construction materials, (ii) standardized leaching protocols that replicate local environmental conditions, and (iii) more stringent occupational exposure guidelines for workers handling FA and SB. Unified frameworks for the safe use of industrial byproducts in construction while reducing toxicological risks can be created with the aid of international cooperation through institutions like the Basel Convention [43].

5. Mitigation and Remediation Strategies

The safe incorporation of coal fly ash (CFA) and sugarcane bagasse (SB) into sustainable brick production requires strategies that minimize heavy metal mobility, reduce environmental contamination, and mitigate toxicological risks to humans and ecosystems. Mitigation and remediation approaches can be broadly categorized into *source reduction*, *stabilization/immobilization*, *process optimization*, and *post-treatment technologies*.

5.1. Source Reduction and Pre-Treatment

Prior to adding CFA and SB to brick production, source reduction entails reducing the amount of heavy metals. It has been demonstrated that pre-treatment techniques like particle size classification, magnetic separation, and acid washing can eliminate surface-bound metals from CFA and lessen leachability [27]. In a similar vein, SB can be pretreated by controlled combustion at 600-700 °C to reduce volatile impurities and unburned carbon, enhancing its pozzolanic quality and decreasing metal solubility [44].

5.2. Stabilization and Immobilization Techniques

The goal of immobilization techniques is to limit the potential for leaching by binding heavy metals within stable mineral matrices. Metals are physically encapsulated by calcium silicate hydrates (C-S-H) and calcium aluminate hydrates (C-A-H),

which are produced by pozzolanic reactions between silica and alumina in CFA/SB and calcium hydroxide [36]. By forming chemically stable phases like zeolites and ettringite, the addition of lime, cement, or geopolymeric binders intensifies this immobilization effect [22]. Alkaline activators have been shown to dramatically lower Pb, Cd, and Cr mobility during brick curing [45].

5.3. Process Optimization in Brick Manufacturing

Metal leaching can be further minimized by improving production conditions. In addition to strengthening the bricks, high-temperature sintering (>1000 °C) reduces the bioavailability of heavy metals by encasing them in vitrified phases [5]. However, high temperatures can cause elements like As and Hg to volatilize more, so firing conditions must be carefully controlled [34]. Other techniques to lower porosity and improve immobilization effectiveness include pressure compaction and longer curing periods.

5.4. Post-Treatment Approaches

Sealants and surface coatings offer an extra line of defense against the leaching of heavy metals. It has been demonstrated that applying silane-based sealers, polymer coatings, or geopolymer surface treatments can lessen metal release and water permeability in harsh environmental settings [7]. Complementary methods for handling contaminated leachates include phytoremediation techniques, in which plants surrounding disposal or storage locations absorb leftover metals [46].

5.5. Circular Economy and Policy Integration

Mitigation calls for integration into a circular economy framework in addition to technical interventions. Risk-based guidelines that take heavy metal toxicity into consideration must be implemented in tandem with regulatory requirements that promote the full use of CFA and SB in construction [27]. Sustainable practices can be guided and environmental trade-offs quantified by establishing life-cycle assessments (LCA) of CFA/SB-based bricks (Yao et al., 2015).

5.6. Future Directions

For improved immobilization, emerging approaches emphasize nanomaterials and sophisticated binders. For instance, by improving hydration products and refining pore structure, graphene oxide and nano-silica have demonstrated promise in lowering leaching [30]. In order to guarantee the long-term stability of immobilized heavy metals, research is also progressing toward the development of adaptive curing regimes that mimic actual climatic conditions.

6. Research Gaps and Future Directions

Despite significant advances in utilizing coal fly ash (CFA) and sugarcane bagasse (SB) for sustainable brick production, several critical research gaps remain that limit the safe and widespread adoption of these materials. First, most studies focus on the mechanical and durability performance of bricks, while systematic investigations into the *long-term leaching behavior of heavy metals under real environmental conditions*—such as fluctuating pH, temperature, and rainfall—are still scarce [1]. Laboratory leaching tests often fail to replicate field-scale complexities, leading to uncertainties in predicting long-term environmental and health impacts. Second, while immobilization mechanisms such as pozzolanic reactions and geopolymerization are well documented, the molecular-scale interactions between heavy metals and hydration products remain poorly understood, requiring advanced characterization techniques like synchrotron-based spectroscopy and high-resolution microscopy [45].

Another gap lies in the limited integration of toxicological and epidemiological data. Although risk assessments frequently quantify hazard indices and lifetime cancer risks, few studies link these findings with actual biomonitoring data from populations exposed to CFA- or SB-based construction materials. Bridging this gap is essential to establish realistic exposure models and validate risk predictions [16]. Moreover, most regulatory frameworks emphasize utilization targets for industrial byproducts but lack risk-based guidelines specifically tailored to sustainable bricks, leaving a policy void that hinders safe large-scale implementation [27].

Looking forward, future research should prioritize field-scale validation of leaching models, incorporating multi-year monitoring of brick structures under different climatic and hydrogeological conditions. Development of novel binders and nanomaterial additives such as nano-silica, bio-char, and graphene oxide holds promise for improving heavy metal immobilization and reducing environmental risks [30]. Additionally, adopting life-cycle assessment (LCA) frameworks will allow researchers to quantify trade-offs between environmental benefits of waste valorization and potential toxicological risks, offering a holistic perspective for policymakers and industry. Collaborative efforts between scientists, regulators, and industry stakeholders will be necessary to design risk-based standards and adaptive regulations, ensuring that the use of CFA and SB in brick production contributes not only to waste minimization but also to human and environmental safety.

7. Conclusion

Reusing sugarcane bagasse and coal fly ash in the production of sustainable bricks has several positive effects on the environment and the economy, such as lowering greenhouse gas emissions, reducing waste, and conserving natural resources. Heavy metals, however, present toxicological risks that need to be carefully evaluated and controlled. According

to scientific data, the majority of heavy metal hazards can be decreased to manageable levels by using suitable stabilization techniques, such as firing, geopolymerization, and cement immobilization. However, to guarantee that the switch to ash-based sustainable bricks is both safe for the environment and healthy for people, more research, stricter regulations, and the application of best practices are necessary.

Abbreviations

CFA	Coal Fly Ash
SBA	Sugarcane Bagasse Ash
SB	Sugarcane Bagasse
HHRA	Human Health Risk Assessment
EPA	Environmental Protection Agency
MoEFCC	Ministry of Environment, Forest and Climate Change
WHO	World Health Organization
LOI	Loss on Ignition
C-S-H	Calcium Silicate Hydrate
C-A-H	Calcium Aluminate Hydrate

Author Contributions

Pratik Krishna: Conceptualization, Investigation, Writing – review & editing

Santosh Verma: Conceptualization, Methodology, Writing – original draft, Writing – review & editing

Conflicts of Interest

The authors declare that they have no conflict of interest regarding the publication of this research work.

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