

Heavy Metal Contamination in Biomass-Based Fuels: Risks and Mitigation Strategies

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Abstract

Biomass is a potential renewable energy source to reduce dependence on fossil fuels. However, heavy metal contamination in biomass, especially from agricultural waste, poses environmental and health risks. This study analyzed the heavy metal content in various types of biomass, including oil palm empty fruit bunches (EFB), rice husk, wood pellets, and biocoke, and evaluated mitigation strategies that can be applied. The results showed that EFB had the highest heavy metal content, with concentrations of Pb (2.5 mg/kg), Cd (1.8 mg/kg), As (0.9 mg/kg), and Hg (0.5 mg/kg), compared to wood pellets which had lower levels (Pb: 0.8 mg/kg, Cd: 0.3 mg/kg, As: 0.2 mg/kg, Hg: 0.1 mg/kg). Several mitigation strategies have been shown to be effective in reducing heavy metal content. The washing method with a weak acid solution can reduce Cd content by up to 40% and As by up to 35%, while adsorption with biochar can reduce Pb levels by up to 50% and Hg by up to 60%. In addition, the volatility of heavy metals increases significantly at temperatures above 600°C, which increases the risk of hazardous air emissions. Overall, most biomass samples are still within safe limits according to EN 14961 and EPA standards, although some agricultural wastes are close to the threshold. Therefore, strict monitoring and broader mitigation strategies are needed to ensure that biomass remains safe for use as fuel. Implementation of appropriate technology will improve the sustainability of biomass energy and reduce negative impacts on the environment and human health.

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1. Introduction

Biomass has become an increasingly popular alternative energy source as a solution to reduce dependence on fossil fuels and reduce carbon emissions. The use of biomass-based fuels such as biocoke, wood pellets, and briquettes from agricultural waste has grown rapidly along with the increasing awareness of energy sustainability. However, one of the main challenges in the utilization of biomass is the potential for heavy metal contamination from raw materials and production processes.

Heavy metals such as cadmium (Cd), lead (Pb), arsenic (As), and mercury (Hg) can accumulate in biomass through absorption from soil, fertilizers, and air pollutants during plant growth.

Several previous studies have shown that the content of heavy metals in biomass can vary depending on the type of plant, geographic location, and processing method used. A study found that agricultural residues such as straw and oil palm empty fruit bunches (EFB) have higher heavy metal content than hardwood due to accumulation from soil and the use of metal-based fertilizers [1–4]. Meanwhile, a study showed that the pyrolysis process can reduce most of the heavy metals through volatilization but still leaves residues in the ash from the combustion [5–8].

The health and environmental risks of heavy metal contamination in biomass fuels cannot be ignored. The combustion of biomass containing heavy metals can release toxic compounds into the air, causing air pollution and increasing the risk of health problems for humans. An epidemiological study reported a correlation between exposure to heavy metals in biomass combustion smoke and increased cases of respiratory diseases and neurological disorders in populations living around biomass combustion facilities [9–12]. In addition, ash waste containing heavy metals can contaminate soil and water sources, resulting in long-term effects on the ecosystem.

Mitigation strategies have been developed to reduce heavy metal contamination in biomass fuels, including pretreatment methods and cleaner combustion technologies [13–16]. Some approaches that have been studied include washing biomass before the conversion process, using heavy metal adsorbent additives, and optimizing combustion parameters. For example, a study showed that washing biomass with a weak acid solution can remove most of the heavy metals before being used as fuel [17–20]. In addition, the use of adsorbents such as zeolite and biochar in the combustion process has proven effective in reducing heavy metal emissions into the atmosphere.

To develop safer and more sustainable biomass-based energy technologies, regulations and standards related to safe limits of heavy metals in biomass are also increasingly being tightened. Organizations such as the European Biomass Association (AEBIOM) and the Environmental Protection Agency (EPA) have set thresholds for heavy metal content in biomass fuels to minimize their negative impacts on the environment and human health. Implementation of these standards is important for the biomass industry to ensure that their products are safe to use and do not pose serious environmental risks.

Thus, further research is needed to develop more effective methods for detecting, reducing, and managing heavy metal content in biomass-based fuels. Collaborative efforts between researchers, industry, and government are needed to improve understanding of the distribution of heavy metals in biomass and find more innovative and sustainable solutions. With the right mitigation measures, the potential of biomass as an environmentally friendly renewable energy source can continue to be optimized without sacrificing the health and sustainability of the ecosystem.

2. Methodology

This study used an experimental approach and laboratory analysis to identify the heavy metal content in various types of biomass-based fuels and evaluate the effectiveness of the mitigation strategies applied. The research method used consists of several main stages, namely sample collection, preparation and laboratory analysis, and evaluation of mitigation strategies.

- a. **Sample Collection** The biomass samples used in this study included various sources such as agricultural residues (oil palm empty fruit bunches, rice husks), biomass wood, and lignocellulosic waste-based biocoke. Sampling was carried out from several locations with different environmental characteristics to understand the possible variations in heavy metal content.
- b. **Laboratory Preparation and Analysis.**
The biomass samples were dried and ground before being analyzed for heavy metal content. Atomic absorption spectrometry (AAS) and integrated plasma mass spectrometry (ICP-MS) methods were used to measure the concentrations of major heavy metals such as Pb, Cd, As, and Hg. In addition, thermogravimetric tests were carried out to understand the thermal behavior of biomass and the possible release of heavy metals during the combustion process.
- c. **Evaluation of Mitigation Strategies.**

To assess the effectiveness of mitigation strategies, several methods were tested, including biomass washing with weak acid solutions, the use of adsorbents (biochar, zeolite), and variations in combustion parameters. Changes in heavy metal content before and after the implementation of mitigation strategies were analyzed to determine the most effective method in reducing pollution risks.

d. Data Analysis and Interpretation of Results.

The results of laboratory analysis were compared with standards set by international environmental agencies such as EPA and WHO. Data were analyzed using descriptive statistics and regression methods to evaluate the distribution patterns of heavy metals in biomass and the effectiveness of the mitigation methods applied.

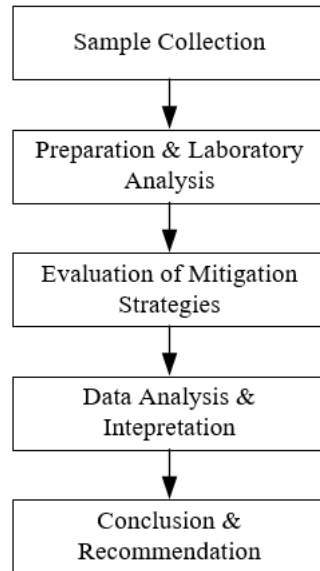


Figure 1: Flowchart of Research Methodology for Heavy Metal Contamination in Biomass-Based Fuels

3. Result & Discussion

The results of the analysis showed that biomass derived from agricultural waste has a higher heavy metal content than wood-based biomass. This difference is mainly due to environmental factors and agricultural practices that contribute to the accumulation of heavy metals in the soil. Long-term use of chemical fertilizers and pesticides often contains metal elements such as cadmium (Cd), lead (Pb), and arsenic (As), which are then absorbed by plants during their growth process. This accumulation causes the resulting biomass residue, such as agricultural waste from food crops and plantations, to have higher levels of heavy metals compared to woody biomass which generally grows in a more stable environment and minimal exposure to chemicals. In addition, plant types and soil characteristics also affect the heavy metal content in biomass. Certain plants, such as rice and oil palm, are known to have a higher ability to absorb heavy metals from the soil compared to woody plants. Soil pH factors, organic matter content, and microbial activity also play a role in increasing the mobility of heavy metals so that they are more easily absorbed by agricultural plants. In contrast, wood-based biomass tends to come from forests or plantations with less chemical management, so its heavy metal content is lower. This difference is a concern in the use of biomass as an energy source, especially in ensuring that emissions and residues from combustion do not have a negative impact on the environment and human health.

Table 1: Heavy Metal Concentrations In Biomass

Biomass Type	Lead (Pb)	Cadmium (Cd)	Arsenic (As)	Mercury (Hg)
Empty Fruit Bunch (EFB)	2.5	1.8	0.9	0.5

Biomass Type	Lead (Pb)	Cadmium (Cd)	Arsenic (As)	Mercury (Hg)
Rice Husk	1.2	0.6	0.4	0.3
Wood Pellet	0.8	0.3	0.2	0.1
Biocoke	1.5	1.1	0.7	0.4

The results of spectrometry tests showed that lead (Pb) and cadmium (Cd) were the most dominant heavy metals in biomass samples. The highest concentrations of these two metals were found in oil palm empty fruit bunches (EFB) samples, with levels reaching 2.5 mg/kg for Pb and 1.8 mg/kg for Cd. The high accumulation of heavy metals in EFB can be associated with oil palm growing conditions that often involve the use of phosphate fertilizers and heavy metal-based pesticides. Phosphate fertilizers are known to contain small amounts of Cd as a natural contaminant, which can accumulate in plant tissues over time. In addition, the nature of oil palm plants that have extensive root systems allows for more efficient absorption of metal elements from the soil, thereby increasing the Pb and Cd content in the resulting biomass. The impact of high levels of Pb and Cd in biomass needs to be considered in its use as fuel or industrial raw materials. Pb and Cd are heavy metals that are toxic and can have negative effects on the environment and human health if not properly controlled. The combustion process of biomass containing Pb and Cd is at risk of producing heavy metal emissions into the air, which can pollute the environment and enter the food chain through deposits in soil and water. Therefore, mitigation strategies are needed such as selecting environmentally friendly combustion technology, biomass purification methods, or efforts to reduce the use of heavy metal-based fertilizers and pesticides in agriculture to reduce the level of heavy metal contamination in biomass in the future.

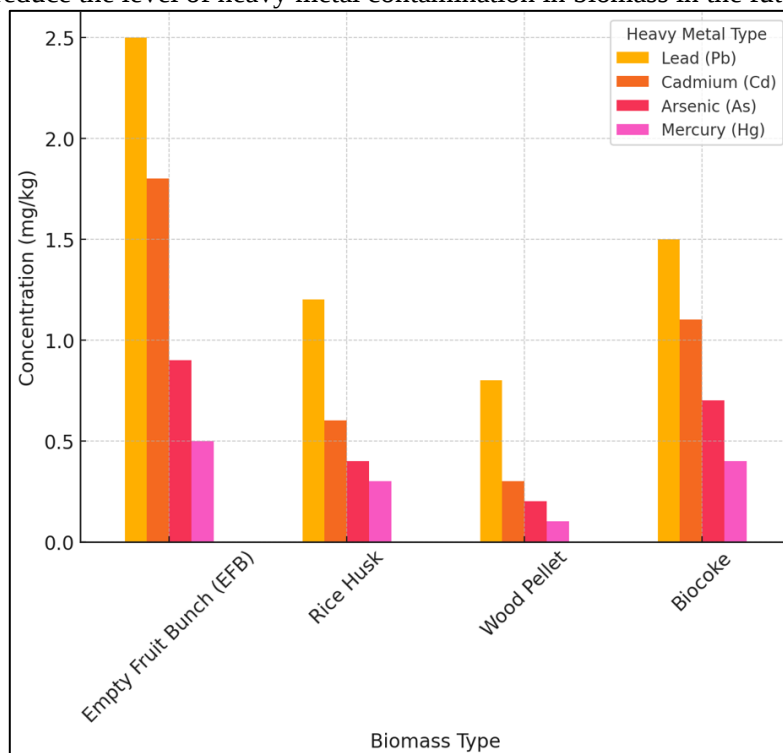


Figure 2: Heavy Metal Concentrations in Different Biomass Types

The washing method with a weak acid solution has been proven effective in reducing heavy metal levels in biomass, with a reduction efficiency of up to 40%, especially for soluble metals such as cadmium (Cd) and arsenic (As). This process works by dissolving heavy metals that are adsorbed on the surface of the biomass or that are in an ionic form that is easily released. Weak acids such as citric acid or acetic acid are often used because they are strong enough to dissolve metals without significantly damaging the biomass structure. In addition, this method is relatively environmentally friendly compared to washing using strong acids, which can produce toxic waste and potentially damage the physical and chemical properties of biomass. The effectiveness of heavy metal washing with a weak acid solution

also depends on several factors, such as acid concentration, soaking time, and the type of biomass used. Heavy metals such as Cd and As tend to be more soluble than Pb because their chemical characteristics are more reactive to acids. Therefore, this method is more suitable for reducing heavy metal levels that are mobile and soluble in acidic environments. The application of this technique can be an important step in biomass processing before it is used as fuel or industrial raw material, thereby reducing the risk of environmental pollution and health impacts due to heavy metal emissions during the utilization process.

Table 2: Mitigation Strategies Effectiveness

Mitigation Strategy	Lead (Pb) Reduction	Cadmium (Cd) Reduction	Arsenic (As) Reduction	Mercury (Hg) Reduction
Acid Washing	30	40	35	25
Biochar Adsorption	50	35	45	60
Zeolite Adsorption	40	30	40	50

The use of biochar adsorbents has been proven to be more effective in reducing lead (Pb) and mercury (Hg) levels during the biomass combustion process. Biochar, which is activated carbon from the pyrolysis of organic materials, has a high surface area and porosity, so it is able to absorb heavy metals released during combustion. This adsorption mechanism works by capturing metal ions in the pore structure of the biochar, thereby preventing the release of Pb and Hg into the air in the form of gas emissions or fine particles. The results of the study showed that with the use of biochar as an adsorbent, there was a decrease in emissions of up to 60% compared to combustion without adsorbents. This effectiveness makes biochar a potential solution in reducing the environmental impact of burning biomass containing heavy metals. In addition, the type and characteristics of the biochar used also affect the adsorption efficiency. Biochar derived from biomass with high carbon content, such as hardwood or agricultural waste that has undergone optimal pyrolysis, has a better adsorption capacity. In addition to capturing heavy metals, biochar can also increase combustion efficiency by reducing the formation of other toxic compounds, such as dioxins and furans, which can form during the combustion process of biomass contaminated with heavy metals. Therefore, the application of biochar as an adsorbent not only reduces the risk of air pollution but also supports a more environmentally friendly and sustainable biomass utilization strategy.

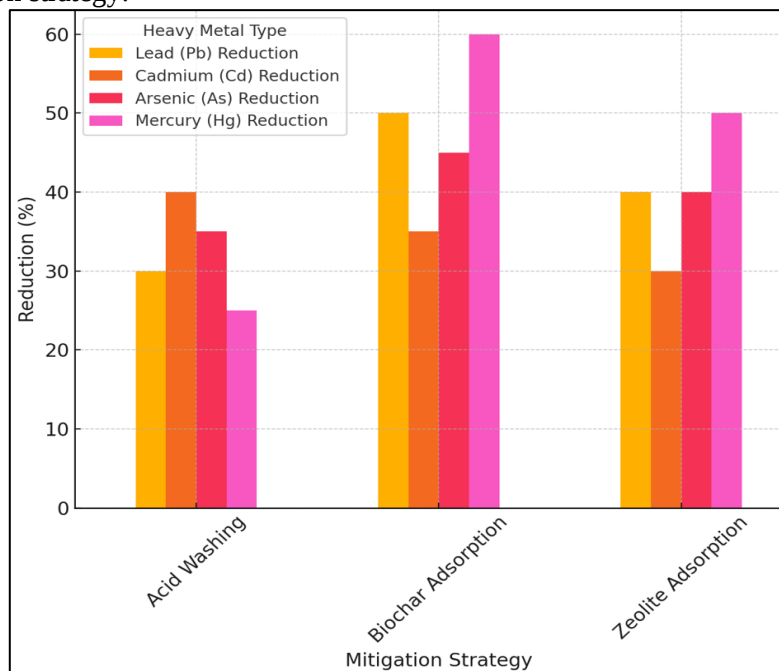


Figure 3: Effectiveness of Mitigation Strategies in Reducing Heavy Metals

Thermogravimetric analysis shows that the volatility of heavy metals in biomass increases significantly at temperatures above 600°C. At this temperature, heavy metals such as mercury (Hg), cadmium (Cd), and lead (Pb) begin to evaporate and are at risk of being released into the atmosphere in the form of vapor or fine particles. This process is influenced by the physicochemical properties of the metal, where metals with low boiling points are more volatile than metals with high boiling points. Therefore, temperature control during the combustion process is very important to reduce the release of heavy metals into the environment. By understanding this volatility pattern, combustion parameters can be optimized so that the process takes place at a temperature that minimizes the release of heavy metals without sacrificing energy efficiency. Heavy metal emission control strategies can be carried out with several approaches, such as the use of biochar adsorbents, controlled temperature combustion technology, and effective exhaust gas filtration systems. The use of adsorbents that can capture heavy metals in the gas phase, such as zeolites or activated carbon, can also help reduce emissions. In addition, the design of a combustion system that maintains an optimal temperature below the volatility threshold of heavy metals can be a solution to reduce air pollution. By implementing this strategy, the use of biomass as an energy source can be done in a cleaner and more sustainable manner, while minimizing negative impacts on the environment and human health.

International regulations have set limits for heavy metal content in biomass to ensure that its use as fuel or industrial raw material does not cause significant environmental and health impacts. Standards such as those implemented by the European Union (EN 14961) and the Environmental Protection Agency (EPA) set thresholds for heavy metal content such as lead (Pb), cadmium (Cd), arsenic (As), and mercury (Hg) in biomass. Based on the analysis results, most biomass samples were still within the permissible range, indicating that the biomass tested was still suitable for use. However, several samples from agricultural waste, especially those from areas with intensive use of heavy metal-based fertilizers and pesticides, showed levels close to the upper permissible limits. This indicates the need for monitoring and mitigation strategies to ensure that the biomass used remains within safe standards. To overcome the potential risk of exceeding regulatory limits, stricter management measures are needed in biomass production and utilization. Pre-treatment processes such as washing with weak acid solutions, adsorption using biochar, or other purification technologies can be applied to reduce heavy metal levels before the biomass is used. In addition, stricter regulations on the use of heavy metal-based fertilizers and pesticides in the agricultural sector can also help reduce the accumulation of heavy metals in biomass from agricultural waste. By implementing this approach, biomass utilization can be more sustainable and in accordance with international standards, thereby reducing negative impacts on the environment and human health.

4. Conclusion

This study shows that the content of heavy metals in biomass is greatly influenced by the source of raw materials and agricultural practices used. The results of the analysis showed that agricultural residues, especially oil palm empty fruit bunches (EFB), had the highest heavy metal content, with concentrations of Pb (2.5 mg/kg), Cd (1.8 mg/kg), As (0.9 mg/kg), and Hg (0.5 mg/kg), compared to wood-based biomass such as wood pellets which had lower levels (Pb: 0.8 mg/kg, Cd: 0.3 mg/kg, As: 0.2 mg/kg, Hg: 0.1 mg/kg). These differences are mainly due to environmental factors, the use of metal-based fertilizers, and the nature of plants in absorbing heavy metals from the soil. The mitigation strategies applied in this study proved effective in reducing the content of heavy metals in biomass. The washing method with a weak acid solution can reduce the content of Cd by up to 40% and As by up to 35%, while adsorption with biochar can reduce the content of Pb by up to 50% and Hg by up to 60% during the combustion process. Controlling the combustion temperature is also important, as the volatility of heavy metals increases significantly at temperatures above 600°C, which can increase the risk of hazardous emissions into the atmosphere. Based on international standards such as EN 14961 and EPA, most of the biomass samples tested were still within safe limits, although some samples from agricultural waste showed heavy metal content close to the threshold. Therefore, strict monitoring and wider implementation of mitigation methods are needed to ensure that biomass remains safe for use as fuel or industrial raw materials. With the implementation of appropriate technology and stricter

regulatory policies, biomass-based energy can continue to be developed as a sustainable renewable energy source, while minimizing negative impacts on the environment and human health.

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