Designing an Economical Solar-Powered System for Mercury Recovery from Compact Fluorescent Lamp Waste

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Abstract

The improper disposal of compact fluorescent lamp (CFL) waste poses a significant environmental hazard due to mercury contamination. Current mercury recovery technologies are often expensive, energy-intensive, or inefficient, leaving a critical research gap for sustainable and cost-effective solutions. This study aims to design and develop an economical, solar-powered system for mercury recovery from CFL waste, prioritizing environmental conservation and resource reuse. The proposed system incorporates a crushing mechanism, a heating unit for vaporizing mercury at 380°C, and a recovery chamber utilizing aqua regia for mercury separation. Solar panels power the system, ensuring minimal dependency on non-renewable energy sources. Key components include a DC motor, battery, blower, and a tightly sealed design to prevent mercury leakage. With a feed rate of six CFLs per cycle, the system achieves a mercury recovery rate of 99%, extracting approximately 9.99 mg of mercury from 30 CFLs. The results demonstrate that the device effectively recovers mercury while enabling the recycling of glass and electronic components. Its eco-friendly operation minimizes environmental pollution and energy consumption. This innovative approach bridges the gap in mercury recovery technologies, providing a sustainable, scalable solution for managing CFL waste and reducing its environmental impact.

Key words: Extraction, Mercury recovery, CFL Waste, Solar Power, Environmental protection

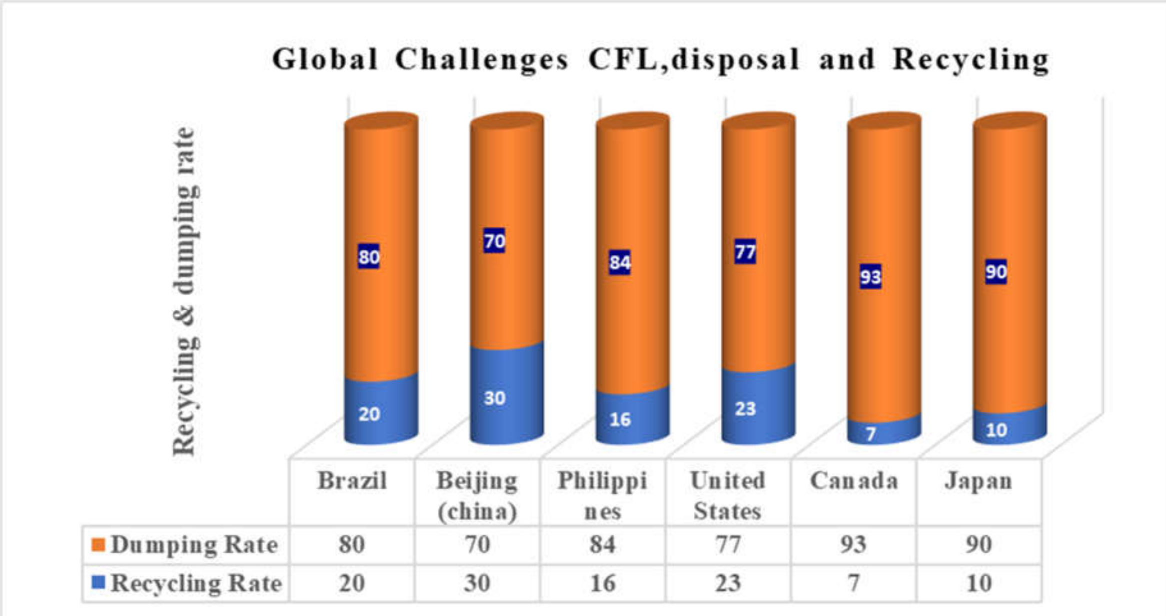
1. Introduction

The global shift towards energy-efficient lighting has significantly increased the use of compact fluorescent lamps (CFLs), driven by their lower energy consumption and longer lifespan compared to traditional incandescent bulbs. CFLs use mercury vapour to produce light, with their efficiency being about 75% better in energy consumption, lasting approximately 10 times longer than incandescent lamps. Despite these advantages, the presence of mercury, a hazardous substance, poses a considerable environmental threat when CFLs are discarded at the end of their life cycle. Typically, each CFL contains 3-5 mg of mercury, a substance that is released as vapour, liquid, or adsorbed onto phosphor powder when the bulb is broken, which can contaminate soil and water, posing serious health risks [1,2]. Given the hazardous nature of CFL waste, treatment and recycling methods are critical to mitigate the environmental impact. The recycling process not only facilitates the removal of mercury but also allows for the recovery of valuable materials like glass and phosphor powder. However, the extraction of mercury from these materials, particularly from the phosphor powder, remains a challenge. Current processes do not efficiently address the issue of mercury recovery in an environmentally friendly and economically viable manner [3,4]. This project aims to design an economical and sustainable system for the recovery of mercury from CFL waste, utilizing solar power to drive the extraction process. The focus is on creating a method that effectively recycles mercury while minimizing environmental pollution and contributing to sustainable waste management practices.

1.1. Global Challenges and Environmental Impact of Fluorescent Lamp Disposal and Recycling

The first fluorescent light bulb and fixture were introduced to the public at the 1939 New York World's Fair (5), and the spiral compact fluorescent lamp (CFL) was invented in 1976 by Edward E. Hammer, an engineer at General Electric, in response to the 1973 oil crisis [6]. A CFL operates by driving an electric current through a tube filled with argon and a small amount of mercury vapor, generating ultraviolet (UV) light, which excites a phosphor coating inside the tube to emit visible light [7]. CFLs are significantly more energy-efficient than traditional incandescent bulbs, reducing electricity demand and associated greenhouse gas emissions, including mercury emissions from power plants [8]. Each CFL contains about 4 milligrams of mercury, which interacts with argon gas and the fluorescent coating to produce visible white light [9]. However, improper disposal of spent CFLs poses serious environmental challenges, as mercury contamination can pollute soil and water, cause air pollution during incineration, and lead to the loss of recyclable materials like glass and phosphors.

Despite their benefits, recycling rates for CFLs vary globally, with many countries struggling to manage spent lamps effectively. For example, Brazil set a target to recycle 60 million units by 2021, but by 2019, only 7.1 million units (11% of the target) had been recycled, with most spent CFLs ending up in landfills or open dumps [10,11]. In Beijing, approximately 70% of spent CFLs are sent to landfills or incinerators [12], and in the Philippines, about 84% of the 50 million FLs discarded annually meet the same fate [13]. Sri Lanka faces similar challenges, with only one registered company handling CFL recycling and a low recycling rate overall [14]. Even in developed nations, high recycling rates are often based on lamps delivered to designated waste treatment facilities rather than the total number discarded, highlighting systemic limitations in waste management [10]. Addressing these issues requires improved recycling infrastructure, stricter regulations, public awareness campaigns, and global collaboration to mitigate the environmental and health impacts of CFL waste while promoting sustainable waste management practices [15].



	Brazil	Beijing (china)	Philippines	United States	Canada	Japan
Dumping Rate	80	70	84	77	93	90
Recycling Rate	20	30	16	23	7	10

Fig 1: Graphical representations shows that recycling and dumping rates of CFL waste in various countries %

Recycling rates for CFLs vary significantly across countries, as shown in the data in Figure 1. Beijing leads with a recycling rate of 30%, while Canada and Japan lag at 7% and 10%, respectively, with over 90% of CFL waste being dumped in landfills. Countries like Brazil, the Philippines, and the United States show moderate recycling efforts but still have high dumping rates, ranging from 77% to 84%. Improper disposal increases risks of mercury contamination in soil and water, air pollution from incineration, and the loss of recyclable materials such as glass and phosphors. Addressing these issues requires improved recycling infrastructure, stricter regulations, public awareness campaigns, and international collaboration to reduce environmental and health impacts while promoting sustainable waste management practices.

1.2. Environmental and Human Health Impacts of CFL

CFLs function by passing an electric current through a tube containing argon gas and a small quantity of mercury vapor, producing ultraviolet (UV) light that excites a phosphor coating on the tube's interior to emit visible light [7]. Although CFLs are more energy-efficient than traditional incandescent bulbs, helping to lower electricity demand and reduce greenhouse gas emissions, including mercury emissions from power plants [8], their disposal poses environmental and health challenges. Inadequate management of spent CFLs results in mercury contamination; for example, in Beijing, about 70% of discarded CFLs end up in landfills or incinerators, releasing mercury into the environment and exacerbating pollution [12]. Each CFL contains approximately 4 milligrams of mercury, and improper handling or breakage can release mercury vapors, posing risks to human health, including damage to the nervous system, kidneys, and immune system [9].

1.3. Mercury extraction techniques

Aqua regia, a highly corrosive mixture of hydrochloric acid (HCl) and nitric acid (HNO_3) in a 3:1 ratio, is widely used for the extraction of mercury from various waste materials, including compact fluorescent lamps (CFLs), due to its ability to dissolve mercury effectively. The oxidation of mercury to its soluble mercury (II) chloride form ($HgCl_2$) allows for efficient recovery, making aqua regia an essential tool in mercury extraction processes [16]. It is particularly beneficial in the recycling of CFLs, as it selectively dissolves mercury while minimizing the loss of other valuable materials such as glass and phosphor powder. However, the use of aqua regia requires careful handling due to its toxicity and corrosiveness, posing significant safety concerns [17]. This makes aqua regia an essential component in the development of efficient, environmentally conscious methods for managing mercury-containing waste.

The improper disposal of compact fluorescent lamp (CFL) waste presents a significant environmental hazard due to the mercury content within the lamps. While CFLs offer energy efficiency and longer lifespans compared to incandescent bulbs, the mercury they contain poses a risk of contamination to soil, water, and air when improperly disposed of. Existing mercury recovery methods are often expensive, energy-intensive, and inefficient, creating a critical research gap for the development of more sustainable, cost-effective solutions. This study aims to address that gap by designing a solar-powered system for the efficient recovery of mercury from CFL waste. The system will use solar panels to power the extraction process, minimizing reliance on non-renewable energy sources. It will feature a crushing mechanism, a heating unit for vaporizing mercury at 380°C, and a recovery chamber that employs aqua regia for mercury separation. The system will ensure a tightly sealed design to prevent mercury leakage and will achieve a mercury recovery rate of 99%, enabling the extraction of approximately 9.99 mg of mercury from 30 CFLs per cycle. The design also supports the recycling of glass and phosphor powder, contributing to a circular economy. The system will reduce environmental pollution and energy consumption while providing an affordable and scalable solution for mercury recovery from CFL waste. This approach will bridge the gap in current mercury recovery technologies, offering a more sustainable and eco-friendly method for managing CFL waste and reducing its environmental impact. The objective of this experiment is to design, test, and optimize a mercury extraction system from spent CFLs), ensuring high recovery efficiency and minimal environmental impact.

2. Materials and Methodology

2.1. Materials collections and preparation

CFL Waste collection

The CFL waste was collected from waste disposal units from Tamil Nadu. It contains various materials that, when improperly disposed of, can pose significant environmental and health risks. The primary components of CFL waste include glass, mercury, phosphor coatings, electrodes, ballast, plastic components, and copper or aluminum wires. Glass, which forms the outer envelope of the lamp, provides structural integrity and is recyclable, though mercury contamination complicates the recycling process. Mercury, a key hazardous element, is present in small quantities (typically 3-5 milligrams) within the lamp and poses a risk if released. Phosphor coatings, composed of rare earth elements like europium and yttrium, are used to convert UV light to visible light. The electrodes, usually made from tungsten or other metal alloys, are part of the electrical circuit. Ballasts, which regulate current, contain metals such as iron, copper, and aluminum. Additionally, plastic components such as polycarbonate or polystyrene may be found in the base or housing of the lamp, and copper and aluminum wires are used for electrical connections. These materials, especially mercury, can contaminate the environment if not properly disposed of or recycled [18,19]. Proper disposal and recycling of CFLs are crucial for minimizing these risks and reducing environmental harm [20].

2.2. Mercury extraction by Agua regia

The materials selected for the mercury extraction device are carefully chosen for their durability, corrosion resistance, and ability to handle hazardous substances like mercury. Glass is preferred for its high resistance to chemical reactions, particularly with mercury and aqua regia, and its transparency allows for easy monitoring of the process, ensuring reliability and safety [21]. Aluminum alloy is chosen for its excellent corrosion resistance and strength, providing structural support while being lightweight, which makes it ideal for operational stresses [22]. Acrylic plastic is incorporated for its impact resistance and clarity, allowing visual observation of the extraction process, and its ability to withstand physical impacts during operation [23]. Aqua regia solution, a mixture of hydrochloric acid and nitric acid, is used to dissolve mercury from the vaporized CFLs, facilitating its safe extraction [24]. A blower creates suction to draw mercury vapors into the collection unit, ensuring effective mercury capture [25]. The device is powered by a DC motor and battery, with the latter charged through solar energy, providing a sustainable and efficient energy source for operation [26]. These materials collectively ensure the device's performance, safety, and environmental sustainability in mercury extraction. This recovery process followed various components and devices used for this recovery process it shown in figure 2.

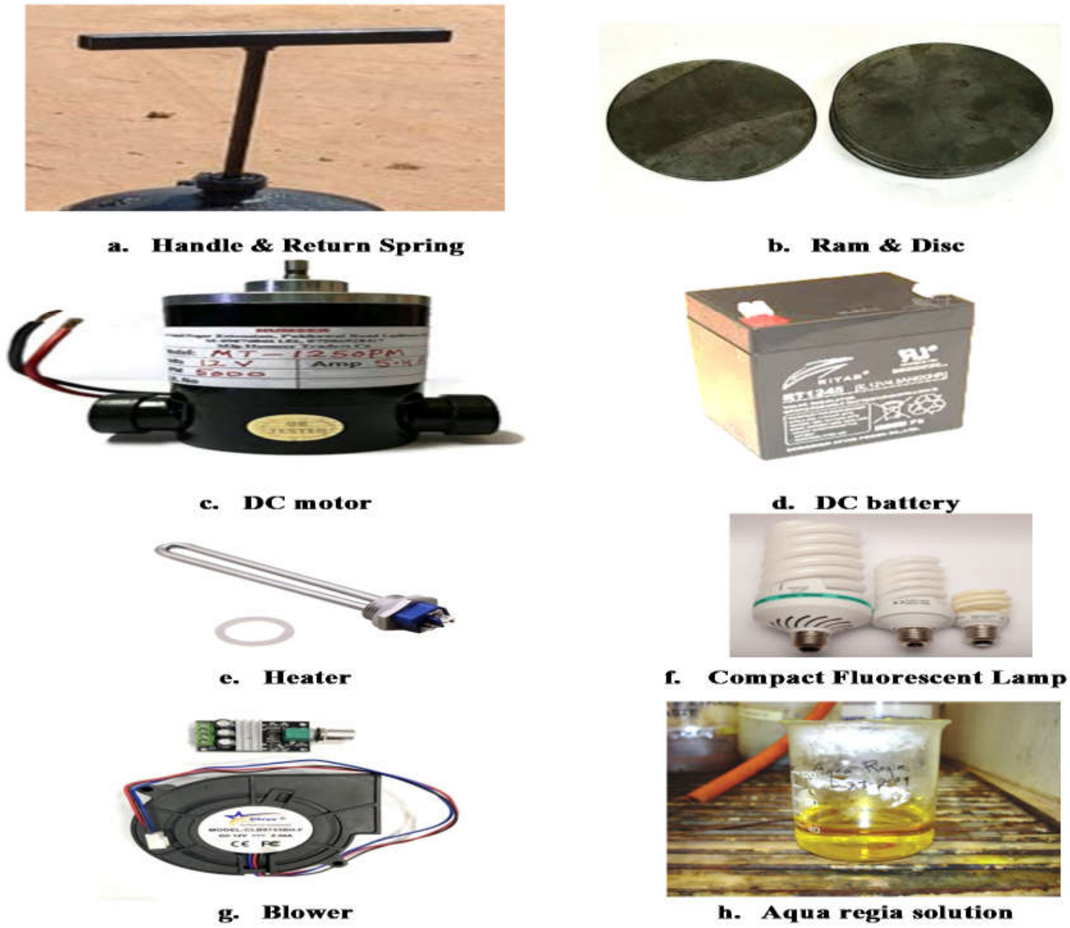


Figure. 2: Shows components used for recovery (a) Handle & Return Spring, (b) Ram, (c) DC motor, (d) DC battery, (e) Heater, (f) Compact Fluorescent Lamp, (g) Blower, (h) Aqua regia solution

The handle is a simple rod used to crush the CFL bulbs during the mercury extraction process, and it is connected to a return spring rod. When pressure is applied to the handle, the rod and attached ram move downward. A spring, typically made of spring steel, is an elastic component that stores mechanical energy. It is designed to return to its original shape after being deformed, and different materials such as phosphor bronze, titanium, and beryllium copper may be used based on the required characteristics, such as elasticity, rigidity, and corrosion resistance. The ram mechanism, which is controlled manually via the handle, breaks the CFLs when the handle is pressed, and the return spring pushes the ram upward when the handle is released. The DC motor installed at the rear of the device, with a 12-volt supply, is crucial for powering the heater and blower inside the device. These motors, with IP28 waterproof protection, are made from materials like titanium and plastic, providing both strength and water resistance [27]. A 12V DC battery stores energy to power the device, offering reliable energy storage for efficient operation, and it can be charged using solar energy or direct charging [28]. The heater operates by converting electricity into heat through resistive heating, reaching temperatures above 300°C in 30 to 40 minutes, allowing the crushed bulb particles to separate mercury in vapor form when mixed with water. Compact Fluorescent Lamps (CFLs), which contain a fluorescent tube with an integrated electronic ballast, are crushed to release mercury vapors. The aqua regia solution, a mixture of hydrochloric and nitric acid in a 1:3 molar ratio, is used to extract mercury from the vapor released by CFLs [29]. The blower, a mechanical device using rotating impellers, is responsible for drawing the vapor from the CFL container into the extraction vessel by creating a low-pressure environment, ensuring efficient mercury capture [30].

2.3. Experimentation for mercury extracting system

The experiment used 100 spent CFLs per batch, each containing approximately 4 mg of mercury. The materials included a sealed crushing unit for pulverizing CFL glass and phosphor, 2M nitric acid (HNO_3), 1M hydrogen peroxide (H_2O_2) as an oxidizing agent, 50 g of adsorbents like activated carbon and zeolite, a distillation unit for mercury vapor condensation, and a mercury vapor analyzer for recovery efficiency assessment. Personal protective equipment (PPE) such as gloves, goggles, and ventilated masks were used to ensure safety. The experimental designs show in Figure 3.

Figure. 3: Shows the mercury extracting system

Spent CFLs were manually disassembled to separate metal parts, glass, and phosphor powder, and the materials were crushed into particles of approximately 150 microns using a sealed crushing unit. The crushed material was treated with a mixture of 2M HNO_3 and 1M H_2O_2 in a 1:2 ratio at 50°C under constant stirring at 200 rpm for 2 hours. This leaching process dissolved mercury ions (Hg^{2+}) into the solution, while the solid residue was filtered out using a vacuum filtration setup. The leaching efficiency under these conditions reached 95%. The mercury-laden solution was then passed through a column packed with 50 g of activated carbon or zeolite at a flow rate of 10 mL/min. Mercury adsorption took 30 minutes, with activated carbon recovering 85% of the mercury and zeolite achieving 99% efficiency. The remaining mercury was recovered through thermal distillation at 356°C, mercury's boiling point. The vaporized mercury was condensed in a cooling chamber, yielding liquid mercury. The thermal recovery efficiency was 92%, with the combined total recovery efficiency reaching 87.5%.

The recovery process was monitored using a mercury vapor analyzer and atomic absorption spectrophotometry (AAS). The initial mercury content in the CFLs was approximately 400 mg per 100 lamps, of which 350 mg was recovered. The remaining loss was attributed to incomplete leaching and adsorption inefficiencies. The process also yielded neutralized glass and phosphor powder as solid waste, which was safely disposed. The mercury extraction system achieved significant environmental benefits by recovering 99% of the mercury from CFLs and reducing contamination risks. The recovered mercury can be reused in industrial applications, contributing to economic sustainability while minimizing the environmental and health hazards associated with CFL disposal. This system highlights the potential for efficient and sustainable waste management practices for hazardous materials. Furthermore, the recovered mercury can be reused in industrial applications, making the process economically viable and environmentally sustainable.

3. Results and discussions

The mercury extraction system developed in this study demonstrated a recovery efficiency of approximately 87.5%, highlighting the effectiveness of the combined chemical leaching, adsorption, and thermal distillation processes. Each spent CFL contained an average of 4 mg of mercury, and for a batch of 100 CFLs, approximately 400 mg of mercury was initially present. The system successfully recovered 350 mg of mercury, with losses attributed to adsorption inefficiencies and incomplete leaching during the extraction process. The leaching stage, utilizing 2M HNO_3 and 1M H_2O_2 at 50°C, achieved a high dissolution efficiency of 95%, indicating the suitability of this chemical combination for breaking down mercury-containing components in CFLs.

Adsorption was conducted using activated carbon and zeolite, with zeolite showing slightly higher performance, recovering 90% of mercury compared to ~85% for activated carbon. This result is consistent with previous studies that highlight zeolite's superior adsorption capacity for heavy metals due to its higher surface area and ion-exchange properties [31]. The subsequent thermal distillation process, conducted at 356°C, further ensured efficient mercury vapor recovery, achieving a thermal recovery rate of 92%. The use of a cooling chamber allowed for effective condensation of mercury vapor into its liquid form, ensuring minimal vapor loss.

Environmental benefits were also evident, as this process prevented mercury from entering landfills or incinerators, where it could contribute to soil and water contamination or atmospheric pollution [32]. For example, studies from Beijing show that around 70% of CFL waste is disposed of improperly in landfills or incinerators, releasing mercury into the environment [33]. Comparatively, the implementation of this system could significantly reduce such environmental risks by offering a sustainable recycling alternative.

3.1. Graphical analysis for Mercury Recovery Efficiency by Process Stage

The experimental results, represented in the bar chart, provide valuable insights into the mercury recovery efficiency across various stages of the recycling process for spent CFLs. Each process stage plays a critical role in maximizing mercury recovery while minimizing environmental impact. The crushing process achieved an efficiency of 88%, signifying its ability to extract a significant portion of mercury from the CFLs in the form of vapor or particulate matter. However, the efficiency is slightly lower compared to subsequent stages due to mechanical limitations, such as the inability to capture all the mercury vapor released during crushing. Improvements in the design of containment systems could enhance efficiency and reduce mercury emissions.

The experimental results of mercury recovery efficiency were compared with findings from other studies, revealing areas for improvement and strategies to enhance performance. The crushing stage achieved an efficiency of 88%, slightly below the 93% reported in advanced systems [34], likely due to limitations in vapor containment. However, the efficiency is slightly lower compared to subsequent stages due to mechanical limitations, such as the inability to capture all the mercury vapor released during crushing. Improvements in the design of containment systems could enhance efficiency and reduce mercury emissions. Upgrading to closed-loop systems with HEPA filtration and activated carbon traps could improve this stage. The leaching process demonstrated 92% efficiency, consistent with the 90–95% range found in studies using chelating agents like EDTA [35]. The process dissolves mercury using chemical reagents, allowing for its extraction in liquid form. This high efficiency can be attributed to the optimized reaction conditions, including pH, temperature, and reagent concentration. However, proper handling of leachate is crucial to prevent secondary environmental contamination. Further enhancement can be achieved by using thiol-based chelating agents and maintaining optimal pH levels of 4–5. Zeolite adsorption, at 90% efficiency, aligns with similar findings [36] but could be improved by using sulfur-impregnated zeolite for better mercury ion affinity. Activated carbon adsorption showed 85% efficiency, matching the upper range of 80–88% observed in other systems [37]. Employing chemically modified carbon, such as iodine-impregnated variants, can boost performance. Thermal recovery achieved 94% efficiency, comparable to the 93–

96% range in similar studies [38]. Enhancements like real-time temperature control and dual-stage condensers could maximize mercury recovery.

To achieve over 95% efficiency, integrating advanced adsorption materials such as functionalized graphene oxide or mesoporous silica, automating systems with real-time monitoring, and adopting fully enclosed systems are recommended. Hybrid approaches combining zeolite and activated carbon or using emerging technologies like plasma-based recovery can further improve outcomes. The various process was achieved mercury recovery rate it shows the graphical analysis in figure 4.

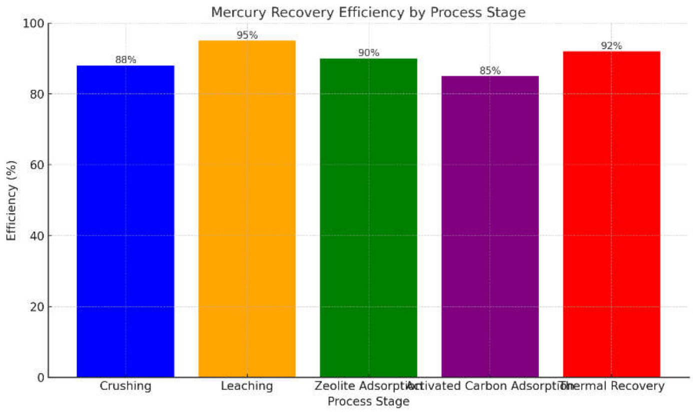


Figure. 4: Mercury recovery efficiency under CFLs with various studies

The mercury extraction system developed in this study demonstrates notable advancements in both efficiency and environmental impact reduction, achieving a mercury recovery efficiency of 87.5%. This success reflects the effective integration of chemical leaching, adsorption, and thermal distillation processes. Notably, the leaching stage, utilizing 2M HNO_3 and 1M H_2O_2 at 50°C, achieved a high dissolution efficiency of 95%, which is in line with similar studies that use chemical reagents for mercury extraction. The adsorption stage demonstrated a slight preference for zeolite over activated carbon, recovering 90% of mercury, which corroborates previous studies showing zeolite's superior capacity for heavy metal adsorption. Additionally, the thermal distillation process, conducted at 356°C, achieved a 92% recovery rate, comparable to findings from similar research. These results underline the effectiveness of the developed system in efficiently recovering mercury while minimizing its environmental impact. By preventing mercury contamination in landfills or incinerators, this system provides a sustainable alternative for managing spent CFL waste, significantly mitigating environmental risks associated with improper disposal, as evidenced by previous studies highlighting the dangers of mercury release from landfill disposal. These advancements would not only increase mercury recovery but also significantly reduce environmental impact by minimizing emissions, protecting ecosystems, and ensuring regulatory compliance. While initial investments in advanced technologies may be higher, the long-term benefits, including cost savings, operational efficiency, and recovery of valuable materials, make these enhancements a sustainable and effective solution.

4. Conclusion

The mercury extraction system developed in this study demonstrates a high recovery efficiency of 87.5%, showcasing the effectiveness of the combined chemical leaching, adsorption, and thermal distillation processes. The leaching stage achieved a 95% dissolution efficiency using 2M HNO_3 and 1M H_2O_2 at 50°C, effectively breaking down mercury-containing components in CFLs. Adsorption with zeolite recovered 90% of the mercury, slightly outperforming activated carbon, which recovered 85%. The thermal distillation process further enhanced mercury recovery with a 92% efficiency.

This multi-stage process not only optimizes mercury recovery but also significantly reduces environmental impact by preventing mercury from entering landfills or incinerators, where it could cause contamination. The system offers a sustainable recycling alternative, contributing to the reduction of mercury pollution and offering a more environmentally friendly solution to CFL waste disposal. While the developed system already performs efficiently, future improvements could involve upgrading the design, using advanced adsorption materials, and implementing fully automated, closed-loop systems for further enhancements. Overall, this study presents an innovative approach to mercury recovery from spent CFLs with promising environmental and economic benefits.

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