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Low-Emission Strategy for the Recycling of Solar Batteries in Ivory Coast: Case of Used Lead-Acid Batteries

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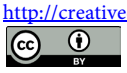


Abstract

This study examines the management of solar battery waste, with a particular focus on used lead-acid batteries. The rise of off-grid solar systems in sub-Saharan Africa is leading to a rapid increase in this waste, whose high lead content poses an environmental and health threat. The objective of this research is to propose a sustainable recycling method based on citric leaching. The experiments yielded yields of 88.23% for lead citrate and 80.02% for lead oxide, confirming the feasibility of this approach in a perspective of sustainable development and local valorization of materials.

Keywords

Electronic Waste, Lead-Acid Batteries, Sustainable Recycling, Leaching, Lead Citrate, Lead Oxide

1. Introduction

Access to electricity in rural areas of sub-Saharan Africa in general and particularly in Côte d'Ivoire is often limited due to the lack of reliable infrastructure [1]. Thus off-grid solar systems, especially solar home devices, have become essential to bridge this gap. Indeed, off-grid solutions have become increasingly popular [2] and, the sale of off-grid solar appliances is recognized as an effective strategy to provide access to electricity for rural households.

However, domesticated solar systems that typically consist of solar panels, charge control system and lithium-ion or lead-acid solar batteries have a short

lifespan, primarily solar batteries. This short lifespan of off-grid solar devices is a hindrance to the goal of providing cheap off-grid solar products to hundreds of millions of people.

In addition, waste batteries have more or less dangerous properties and therefore require special treatment and disposal processes. Regarding lead-acid batteries, these off-grid solar device components have a very short lifespan and therefore occupy the largest and most toxic waste fraction because about 65% of the weight of a lead-acid battery consists of lead (and lead oxide) [3] which is a cumulative neurotoxin, known to impact human brain function and development at low levels of exposure, and is lethal at high concentrations [4]. Lithium-ion batteries used in off-grid solar installations (manganese oxide and iron phosphate and lithium) are considered to have low toxic potential but contain critical raw materials: lithium and graphite, classified as of critical economic importance while facing supply risks [5].

It is therefore urgent to establish viable strategies for the treatment of these waste solar batteries in general and specifically waste lead-acid batteries. Unfortunately, the treatment of these waste lead acid batteries requires specific recycling processes such as the reduction smelting process using infrastructures that do not exist in some developing countries [6]. Moreover, the traditional methods of recycling used lead-acid batteries are based on the pyrometallurgy process [7] for which the emissions of sulfur oxides, of nitrogen oxides and particles containing lead constitute a serious consequence for the local environment and human life and the electrodeposition process which although having been perceived as a more environmentally friendly alternative to pyrometallurgy is nevertheless a way very energy-consuming and, in the medium and long term may not be economically viable for a commercial application due to costs and also indirect emissions associated with purchased electricity if the source is based on fossil fuels.

Unlike pyrometallurgical recycling methods that emit significant amounts of sulphur oxides (SO_x), nitrogen oxides (NO_x) and particulate matter containing lead, citric acid leaching is carried out at ambient temperature and pressure, without combustion of fossil fuels. This hydrometallurgical process significantly reduces emissions of greenhouse gases and toxic substances, while limiting the production of solid waste and avoiding secondary pollution associated with high-temperature processes.

Thus, in such a context, it is necessary to research innovative methods of processing used lead-acid batteries, aiming at providing environmental benefits and reduced energy consumption.

Faced with this worrying situation, we have set ourselves the objective of valorizing the lead paste recovered in used lead-acid batteries.

Specifically, it will be for us to transform this lead paste into lead oxide PbO II, constituting used in the development of electrodes of lead-acid batteries.

2. Methodology

The process begins with battery disassembly. The plastic casing must be carefully

removed using appropriate tools, then the electrodes separated and the lead paste recovered with a spatula, placed in a porcelain crucible. The recovered lead paste must be crushed to obtain a fine powder, then sieved to ensure homogeneous particle size. For leaching, a citric acid solution and a sodium citrate solution must be prepared. Then, in an Erlenmeyer flask, mix these solutions with the pretreated lead paste. Use a magnetic stirrer to maintain agitation and slowly add the hydrogen peroxide to the slurry to reduce lead IV oxide to lead II oxide, while observing the appearance of lead citrate crystals. After the reaction, filter the solution to separate solid precipitates from the liquid. Place the precipitate in an air oven to remove moisture, then put the resulting lead citrate in an electric furnace for thermal decomposition. After calcination, recover the formed lead oxide and weigh the resulting lead oxide samples to evaluate the process performance.

3. Material

The materials used include waste lead-acid batteries, citric acid, sodium citrate and hydrogen peroxide. Laboratory equipment includes precision scales, magnetic stirrers, and electric furnaces.

3.1. Support D'étude

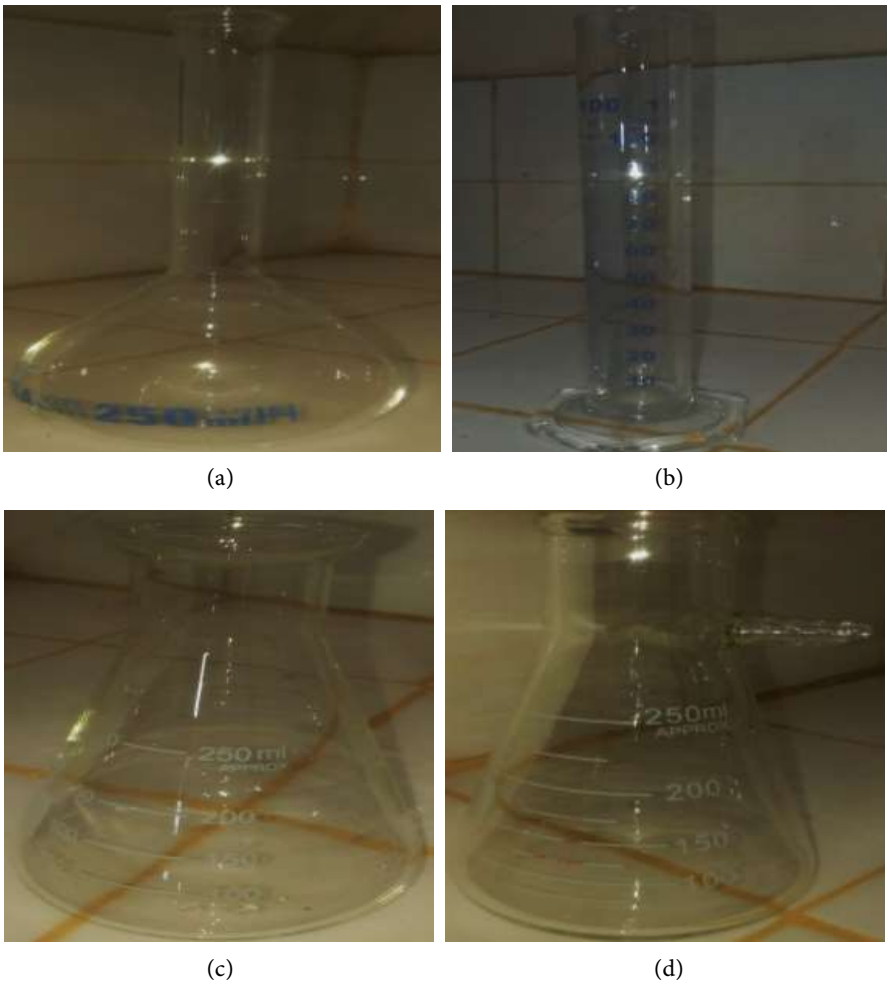
As part of our work, the study support consists of used batteries. It is a spent battery type PowerSafe SBS-B8 VRLA 12.0 V 31.0 Ah (Figure 1). It is said to be waterproof, since its electrolyte is absorbed and immobilized between each plate by cellulose (a kind of blotting paper). It is generally used for solar-type applications. This battery consists of three compartments connected in series and connected by soldered lead connections. Each compartment is composed of a set of couples of positive lead oxide IV (PbO_2) and negative lead (Pb) electrodes connected in parallel, the electrodes are separated by a paper and bathed in an electrolyte solution of sulphuric acid H_2SO_4.

Figure 1. Used lead acid battery (12 V voltage and 31 Ah capacity).

3.2. Chemical Material

3.2.1. Glassware

Glassware is the one commonly used in laboratories. These include, among others, 250 mL volumetric flasks, various pipettes and insets, and 100 mL graduated cylinders for measuring solvent volume and preparing solutions, erlenmeyer flasks for leaching, and vacuum flasks for vacuum filtration. Figures 2(a)-(d) illustrate the essential instruments for the preparation and manipulation of solutions in the context of our experiments.



(a) (b)

(c) (d)

Figure 2. Laboratory glassware. (a) fiole jaugee de 250 mL, (b) eprouvette graduee de 100 mL, (c) erlenmeyer de 250 mL, (d) fiole video at 250 mL.

3.2.2. Reagents and Solvents

All the chemicals used are of pure analytical quality and prepared with distilled water, they are solutions of citric acid and sodium hydrated citrate of respective molar concentrations 2.5 mol·L^{-1} and 1 mol·L^{-1} then a 30% purity hydrogen peroxide solution. All the experiments were carried out at room temperature (1˚C - 25˚C). Figures 3(a)-(c) show the chemicals used for the preparation of solutions needed for experiments.

(a) (b) (c)

Figure 3. Chemical reagents. (a) Bottle containing crystals of hydrated citric acid ($C_6H_8O_7H_2O$) with a purity of 98%, (b) Vial containing crystals of sodium citrate hydrate ($Na_3C_6H_5O_7{\cdot}2H_2O$) with a purity of 98%, (c) Bottle containing a 50% purity hydrogen peroxide solution.

3.3. Laboratory Equipment

The leaching and recovery process of lead oxide requires the use of several specialized laboratory equipment to ensure the accuracy and efficiency of operations. The equipment used are as follows:

- An OHAUS brand precision balance 0.1 mg used to make high-precision mass measurements (**Figure 4(a)**).

(a) (b)

(c) (d)

Figure 4. Laboratory equipment. (a) Precision balance (Maximum load 200 g, sensitivity 0.1 mg), (b) magnetic stirrer (speed continuously adjustable from 0 to 2000 rpm., Plate diameter: 120 mm.), (c) Air oven (Voltage: 230 V, 50 - 60 Hz, Power: 600 W, Content: 14 L, Temperature range: 220˚C), (d) Electric oven (Volume: 15 liters, Max temperature: 1200˚C).

- A STIRRER brand magnetic agitator used to ensure homogeneous mixing of the reagents, agitation constante of the solution and ensure uniform distribution of the reagents for chemical reaction efficiency by maintaining continuous movement in the solution (**Figure 4(b)**).
- A filtering system, used for the separation of solid precipitates from the liquid solution, thus allowing the elimination of unwanted solids while recovering the precipitates formed during the reaction.
- A Memmert air oven with adjustable temperature, used for sample drying and ensuring controlled evaporation of water without altering the precipitate structure (**Figure 4(c)**).
- A Nabertherm brand calcination oven, allowing the thermal decomposition of samples at a precise temperature (**Figure 4(d)**).

4. Procedure

4.1. Dismantling of the Battery and Recovery of Lead Paste

Battery dismantling must be carried out carefully to ensure safety and efficient recovery of components. It is essential to use appropriate tools, such as a saw, knife and hammer, to avoid damaging the internal components. It is advisable to start by carefully removing the plastic case from the battery in order to preserve the electrodes and lead paste. Once the housing is removed, the positive and negative electrodes must be gently separated to avoid any short circuit or accidental discharge. Then it is necessary to use a spatula to recover the lead paste, ensuring that it is placed in a porcelain crucible for the next processing step. It is also important to ensure appropriate protection to avoid contamination or exposure to toxic substances contained in batteries, such as lead and sulfuric acid.

4.2. Pretreatment of Recovered Lead Paste

After separation of the electrodes and recovery of the lead paste, it is ground and then sieved to obtain a fine powder with homogeneous particle size. The recovered and pretreated lead paste is composed of 60% by weight of lead sulfate ($PbSO_4$), but also lead dioxide (PbO_2), about 26.5% by weight, lead oxide (PbO), 9.5% by weight and finally metallic lead (Pb) about 4% by weight [8]. The synthesis of lead citrate (II) is a key step to convert this paste into a precursor that, by thermal decomposition, will produce lead oxide (PbO). This protocol describes the complete procedure, from dismantling the battery to obtaining lead oxide (PbO).

4.3. Preparation of Leaching Reagents

The 250 mL preparation of 2.5 mol·L^{-1} citric acid solution required the withdrawal of 131.25 g of the hydrated citric acid crystal, the 1 mol·L^{-1} sodium citrate solution was prepared with a mass of 73.5 g of hydrated sodium citrate. The concentrations of 2.5 mol/L for citric acid and 1 mol/L for sodium citrate were selected based on previous studies that demonstrated their effectiveness in dissolving lead compounds while maintaining a moderate acidity that limits unwanted side reactions. These concentrations ensure good leaching kinetics without excessive consump-

tion of reagents, thus contributing to the environmental and economic viability of the process. Finally, the withdrawal of a volume of 150 mL of 50% hydrogen peroxide solution was necessary for the preparation of 250 mL of 30% hydrogen peroxide.

4.4. Synthesis of Lead Citrate

4.4.1. Reaction of Lead Paste with Leachate Constitutes Solutions of Citric Acid and Sodium Citrate

The recovered and pretreated lead paste was dissolved in an Erlenmeyer flask containing 18 mL of a 2.5 mol citric acid ($C_6H_8O_7H_2O$) solution·L^{-1} and 26 mL of a 1 mol·L^{-1} sodium citrate ($Na_3C_6H_5O_7{\cdot}2H_2O$) solution. The chemical reactions resulting from this process are given by the following equations:

$$PbO + C_6H_8O_7 \cdot H_2O \rightarrow Pb\left(C_6H_6O_7\right) \cdot H_2O + H_2O \quad (1)$$

$$\begin{aligned} &3PbSO_4 + 2Na_3C_6H_5O_7 \cdot 2H_2O + C_6H_8O_7 \cdot H_2O \\ &\rightarrow 3Pb\left(C_6H_6O_7\right) \cdot H_2O + 3Na_2SO_4 + 2H_2O \end{aligned} \quad (2)$$

4.4.2. Reduction of Lead Oxide IV (PbO_2) with Hydrogen Peroxide

Hydrogen peroxide (H_2O_2) at 30% has been added slowly to the previous slurry to reduce lead oxide IV (PbO_2) to lead oxide II (PbO), facilitating the complete formation of lead citrate II. The addition of hydrogen peroxide must be done in a small amount to avoid a violent reaction. The chemical reaction resulting from this process is given by the following equation:

$$PbO_2 + C_6H_8O_7 \cdot H_2O + H_2O_2 \rightarrow Pb\left(C_6H_6O_7\right) \cdot H_2O + O_2 + 2H_2O \quad (3)$$

4.5. Transformation of Lead Citrate into Lead Oxide

After the reaction, the solution is filtered to separate solid precipitates from the liquid. Then the precipitate should be placed in an air oven at a controlled temperature to remove moisture. Once this step is completed, the resulting lead citrate is placed in an electric furnace set at 405˚C to proceed with thermal decomposition. After calcination, the lead oxide formed can be recovered.

5. Results and Discussions

5.1. Study Results

5.1.1. Lead Paste Recovered from the Dismantled Battery

As shown in **Figure 5**, the dismantling of the battery has been successfully completed, allowing the recovery of essential components necessary for the synthesis of lead oxide. After carefully removing the plastic housing, the positive and negative electrodes were carefully separated, minimizing the risk of short circuit. The lead paste was efficiently extracted using a spatula and placed in a porcelain crucible (**Figure 6**). This recovered paste was then ground and sieved to obtain 10 g of fine-grained lead paste (**Figure 7**). The process took place in compliance with safety standards, ensuring the integrity of materials and safe handling of potentially toxic substances.

Figure 5. Photograph of the dismantled battery.

Figure 6. Photograph of unpretreated lead paste.

Figure 7. Pretreated lead paste on a mass balance 10 g.

5.1.2. Appearance of Lead Citrate Crystals

Leaching is carried out under magnetic agitation at a speed of 650 rpm for five minutes to maintain the total slurry suspension at room temperature (**Figure 8**).

Figure 8. Photograph of the first stage of leaching of lead paste on a magnetic shaker (black solution).

The first crystals of white-colored lead citrate began to appear immediately after the addition of hydrogen peroxide following a violent exothermic reaction (**Figure 9**). The total transformation of lead oxide into lead citrate was observed after 2 min. This reaction ended as indicated in **Figure 10** by the observation of the absence of the appearance of new crystals of lead citrate.

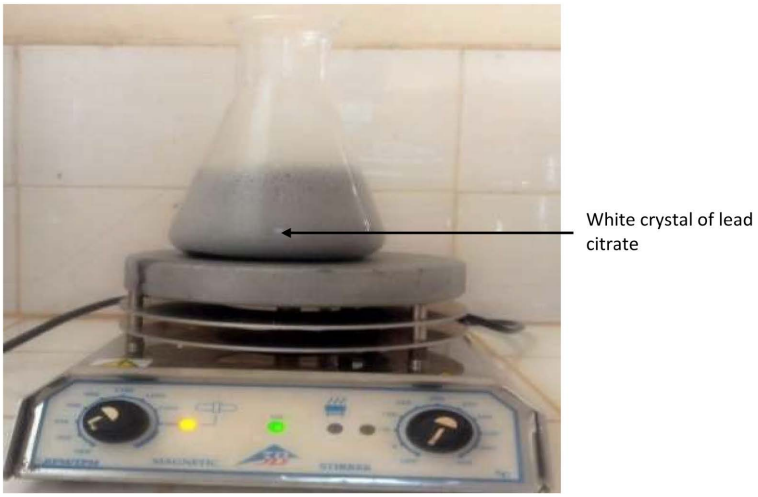


Figure 9. Change in leachate coloration indicating the appearance of the first crystals (white) of lead citrate.

Figure 10. End of the leaching reaction.

5.1.3. Lead Citrate Synthesized and Calcined into Lead Oxide

After filtration, and oven drying of the precipitate, 12.9 g of white lead citrate powder could be collected (Figure 11). The synthesized lead citrate was then placed in an electric furnace at 405˚C or its thermal decomposition allowed to synthesize 5.3 g of yellow-colored lead oxide (Figure 12).

Figure 11. Photographie du citrate de plomb synthétisé sur une balance masse 12.9 g.

Figure 12. Photographie de l'oxyde de plomb synthétisé sur une balance masse 5.3 g.

5.1.4. Efficiency of Transformation of Lead Paste into Lead Oxide

- *Efficiency of the leaching process*

The leaching process made it possible to synthesize a mass of 12.9 g of lead citrate on a theoretical mass of 14.62 g expected, which corresponds to a leaching yield of 88.23%.

- *Efficiency of thermal decomposition of lead citrate*

From the thermal decomposition of lead citrate, 5.3 g of lead oxide were formed over an expected 6.62 g which corresponds to a yield of 80.02%.

5.2. Discussion

5.2.1. Analysis of the Leaching Process of Used Lead Paste

The leaching process showed notable efficiency with a yield of 88.23%. This obtained result indicates an efficient conversion of lead paste into lead citrate whose thermal decomposition will produce lead oxide.

5.2.2. Analysis of Thermal Decomposition of Lead Citrate into Lead Oxide

The thermal decomposition of lead citrate at 450˚C has also been successful. The return of 80.02% is in line with expectations, although it is slightly below 100%. The losses observed can be attributed to volatilization of some organic by-products and partial carbonization of lead citrate during the calcination process.

Losses are mainly due to volatilization and carbonization of intermediates during calcination. To minimize these losses, it is suggested to optimize the calcination temperature (ideally between 380˚C and 400˚C) and extend the treatment time in order to ensure complete decomposition without overheating. Controlling the heating rate and using a covered crucible can also limit losses by volatilization.

Furthermore comparatively, previous studies have reported yields of up to 97.86% for similar processes [9]. This suggests that, while effective, the method employed could benefit from further optimization, particularly in controlling reaction parameters and experimental conditions to minimize losses.

5.2.3. Desulfurization of Used Lead Paste

Lead sulphate, which makes up about 60% by weight of the used lead paste, is a very stable compound that does not react with common acids such as hydrochloric acid, nitric acid or acetic acid. Therefore, a key pre-treatment is to desulphurize lead sulphate into more reactive compounds such as lead citrate. The pH of the leaching solution plays a dominant role in this process, as too high a pH can lead to the formation of layers of lead citrate that cover the lead sulphate, thus inhibiting its desulphurisation. Conversely, a lower pH promotes the dissolution of these layers, exposing more lead sulfate to the reaction [10]. In the leaching system used, composed of citric acid and sodium citrate, citric acid acts both as a pH adjuster and as an agent involved in the crystallization of lead citrate. During our experiment, these conditions made it possible to efficiently transform the lead sulphate contained in the spent pulp into lead citrate, with a mass obtained of 12.6 g and a yield of 88.23% compared to the theoretical mass of 14.3 g. This performance, close to ideal, reflects a good efficiency of the leaching system, despite minimal losses attributed to the filtration and washing steps, as well as the complexity of the initial lead paste, which contains impurities. These results confirm the effectiveness of the method based on citric acid/sodium citrate solution for lead recovery in the form of lead citrate, thus validating the theoretical principles described.

6. Limits of the Study

This study was carried out on a single type of valve-regulated lead-acid battery (PowerSafe SBS-B8, 12 V, 31 Ah) at the laboratory scale. Therefore, the reproducibility and scaling of the process still needs to be assessed. Future research should include pilot-scale and other battery tests to assess the robustness and adaptability of the method.

7. Conclusions

This study made it possible to propose and test an innovative and environmentally friendly method for the recycling of used lead-acid batteries, based on citric acid leaching. The results obtained showed that the process is efficient, with yields of 88.23% for the synthesis of lead citrate and 80.02% for the production of lead oxide. These values confirm the feasibility of the process and its potential for application in a context of local recovery of hazardous waste.

From an environmental perspective, this approach is a low-emission strategy as it does not require combustion or high temperatures, unlike conventional pyrometallurgical processes. It significantly reduces emissions of toxic gases such as sulfur oxides and lead particles, while limiting energy consumption. Moreover, it promotes circular recycling compatible with sustainable development objectives.

However, some limitations of the study should be noted. The experiments were conducted at laboratory scale on a single type of battery (PowerSafe SBS-B8 VRLA), which limits the generalization of the results. Additional work on a larger scale and on other types of lead-acid batteries will be required to validate the reproducibility, stability and performance of the process under industrial conditions.

From an economic point of view, citric acid leaching has interesting potential for Côte d'Ivoire. The cost of reagents used remains relatively low, and their partial regeneration could further reduce operational expenses. At the same time, the market value of recovered lead oxide offers an opportunity for profitability, especially in a context where recycling infrastructure is limited. This process could thus contribute to the creation of green jobs and the development of a local sustainable recycling sector.

Finally, lixiviation with citric acid stands out as an ecological, technically feasible and potentially profitable alternative for the recycling of used lead-acid batteries in Ivory Coast. Future studies on the optimization of reaction parameters and industrial scale-up will strengthen the viability and impact of this approach in the country's energy transition.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

References

[1] Blimpo, M.P. and Cosgrove-Davies, M. (2019) L'accès à l'électricité en Afrique subsaharienne: Adoption, fiabilité et complémentarité des facteurs d'impact économique.

[2] AIE (2019) Perspectives énergétiques de l'Afrique 2019—Scénarios d'analyse Perspectives énergétiques mondiales, 288.

[3] Manhart, T., Hilbert, I. and Magalini, F. (2018) Gestion de la fin de vie des batteries dans le secteur de l'énergie solaire hors réseau.

[4] Rees, N. and Fuller, R. (2020) La vérité toxique: L'exposition des enfants à la pollution par le plomb compromet le potentiel d'une génération.

[5] Commission (2020) Communication de la Commission au Parlement européen, au

Conseil, au Comité économique et social européen et au Comité des régions. Résilience des matières premières critiques: Tracer la voie vers plus de sécurité et de durabilité.
https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:DC&from=EN

[6] Magalini, F., Sinha Khetriwal, D. and Munyambu, S. (2017) Analyse coûts-avantages et évaluation des capacités pour la gestion des déchets électroniques (e-déchets) dans le secteur des énergies renouvelables hors réseau au Kenya.

[7] Prengaman, R.D. (1995) Recovering Lead from Batteries. *JOM*, **47**, 31-33. https://doi.org/10.1007/bf03221127

[8] Santos, S.M., Neto, J.C. and Silva, M.M. (2019) Forecast Model to Evaluate the Potential for Secondary Lead Production from Lead-Acid Battery Waste. *Environmental Science and Pollution Research*, **23**.
https://scholar.google.be/citations?view_op=view_citation&hl=en&user=axguR5IAAAAJ&citation_for_view=axguR5IAAAAJ:4JMBOYKVnBMC

[9] Sonmez, M.S. and Kumar, R.V. (2009) Leaching of Waste Battery Paste Components. Part 1: Lead Citrate Synthesis from PbO and PbO_2. *Hydrometallurgy*, **95**, 53-60. https://doi.org/10.1016/j.hydromet.2008.04.012

[10] Arora, P. and Zhang, Z. (2004) Battery Separators. *Chemical Reviews*, **104**, 4419-4462. https://doi.org/10.1021/cr020738u