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Comparative assessment of button cells using a normalized index for potential pollution by heavy metals

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HIGHLIGHTS

- We compare the polluting potential of button cells using an energy-normalized index.
- This battery index considers both chemical composition and energy content data.
- Environmental impact can be reduced by selecting batteries with a low index value.
- Alkaline, zinc-air, silver oxide and lithium batteries show different index values.
- Index values also vary among brands for batteries with the same technology.

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ABSTRACT

Many household batteries worldwide still end up in landfills or are incinerated due to inefficient collection and recycling schemes. Toxic heavy metals from improperly discarded button cells pose a serious risk to human health and the environment, as they can pollute air, soil and water. This paper analyses a series of button cells selected from batteries available on the retail market, and compares their polluting potential. A total of 64 batteries were subjected to chemical analyses of 19 elements — including metals and metalloids — , and energy density measurements. The samples were from four different brands of each of the four most common button cell technologies (alkaline, zinc-air, silver oxide and lithium). An energy-normalized index — the Weighted Potential Pollution Index (WPPI) — was proposed to compare the polluting potential of the different batteries. The higher the battery WPPI score, the greater the content in toxic elements and the lower the energy output. The results of the chemical composition and energy density varied depending on the construction technology of the button cells. However, significant differences in both variables were also found when comparing different brands within the same technology. The differences in WPPI values confirmed the existence of a significant margin to reduce the environmental impact of discarded button cells simply by avoiding the most polluting options. The choice of the battery with the most favourable WPPI produced a reduction in potential pollution of 3–53% for silver oxide batteries, 4–39% for alkaline, 20–28% for zinc-air and 12–26% for lithium. Comparative potential pollution could be assessed when selecting batteries using an energy-normalized index such as WPPI to reduce the environmental impact of improperly disposed button cells.

1. Introduction

Batteries are a source of compact electrical energy that allow electronic devices to operate without the need to connect them to the mains. The perfect battery (Buchmann, 2001) should simultaneously have high energy density, no internal resistance, no self-discharge, a flat discharge curve, and be free of any substance capable of polluting the soil or water once it is discarded. This last requirement is probably the most difficult to fulfil. There is no such thing as a perfect battery, and this is the reason for the wide range of different technologies on the market, each with advantages and drawbacks (Linden and Reddy, 2002). Button cells — also known as coin cells — are among the most commonly used battery formats. They are defined as "any small round portable battery or accumulator whose diameter is greater than its height and which is used for special purposes such as hearing aids, watches, small portable equipment and back-up power" (EC, 2006). From a chemical point of view, the four most widespread technologies among primary button cells — that is, non-rechargeable batteries — are lithium, zinc-air, alkaline and silver oxide. Although they have very different chemical compositions, all four contain heavy metals in relatively high quantities (Linden and Reddy, 2002).

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Heavy metals are considered conservative pollutants, in that they are not readily broken down or destroyed in the environment, although they are often immobilised in the solid matrix of the terrain (Alloway, 2013). As most heavy metals are toxic elements, improper disposal of discarded batteries poses a serious risk to human health and the environment (Jarup, 2003; Lindqvist, 1995; Mukherjee et al., 2004). Many countries have legislated on the manufacture and disposal of batteries (EC, 2000, 2006; Guevara-García and Montiel-Corona, 2012; Smith and Gray, 2010; USC, 1996). Regulated issues include special labelling, limit values for maximum contents, and even prohibition of certain heavy metals such as mercury, lead, cadmium or nickel, as well as selective collection, controlled dumping and recycling of used batteries. The main efforts have focused on phasing out the use of mercury (EC, 2008; Kim and Choi, 2012), although the production of button cells is one of the remaining uses of mercury in the European Union (EU; BIO Intelligence Service, 2012). Although manufacturers are beginning to market mercury-free versions of button cells (Galligan and Morose, 2004), these battery formats are still permitted to contain up to 2% of their weight in mercury in the EU (EC, 2006), and some commercially available batteries in the EU have been shown to exceed this limit value (Recknagel et al., 2014).

The most worrying issue is that consumption of batteries is on the rise, and rates of uncontrolled dumping remain very high. Many batteries worldwide still end up in landfills or are incinerated due to inefficient national collection and recycling schemes (Smith and Gray, 2010). The European Portable Battery Association reported that sales of button-type batteries in the European Union increased by 29% between 2004 and 2010. According to the 2012 European Commission report (BIO Intelligence Service, 2012), 1.08 billion button-type batteries were sold in the European market in 2010, of which only 39% were mercury-free. 2009 statistics show that approximately 88% of discarded button cells escaped separate waste collection schemes and ended up with mixed non-hazardous waste (BIO Intelligence Service, 2012). As non-hazardous waste treatment methods are not designed for battery waste, the release of heavy metals into air, water and soil is totally uncontrolled. In view of the urgent need for a drastic reduction in heavy metal emissions into the environment, the Batteries Directive goal (EC, 2006) of collecting 45% of the batteries used in European countries by 2016 seems insufficient. Limited information is available on reported recovery rates for consumer batteries in other countries, but published figures do not suggest a much better overall scenario (Bernardes et al., 2003; Kelleher Environmental, 2009; Zand and Abduli, 2008). In the meantime, additional measures such as reducing the heavy metal contents in the batteries on the market could help mitigate negative impacts on human health and the environment.

Given current battery technologies, is it possible to produce button cells containing lower amounts of toxic elements without reducing the energy output of the battery? This can be done for mercury (EC, 2008), although owing to the lack of published studies on this issue in the case of most heavy metals this question is still unanswered. There are a few recent publications on the chemical composition of button cells (Recknagel et al., 2014; Richter et al., 2008) and other household batteries (Guevara-García and Montiel-Corona, 2012; Barrett et al., 2012); however, these papers focus only on a limited number of components (such as mercury, cadmium and lead) and do not include energy density values.

The main goals of this work are to analyse the chemical composition and energy density of a series of button cells available on the retail market and compare their polluting potential. We studied and compared batteries from the four most common button-cell technologies (alkaline, zinc-air, silver oxide and lithium). This paper reports the chemical analyses of 19 elements — metals and metalloids — and energy density measurements from a total of 64 batteries. An energy-normalized index — the Weighted Potential Pollution Index (WPPI) — is proposed to compare their polluting potential. This index takes account of the fact that when a battery contains less energy, more batteries will be required to operate a particular device, and more will be dumped into the environment. In common with both the grey water footprint concept (Hoekstra et al., 2011) and the critical dilution volume approach (EC, 1995), WPPI expresses potential pollution in terms of the theoretical maximum volume of polluted water. As WPPI is intended to be a simple tool for the comparative evaluation of button cells, we avoided the complexity of other methodologies such as the multimedia characterization models used in environmental risk assessment (EC, 2004; Rosenbaum et al., 2011; Van Hoof et al., 2011). The WPPI values for the batteries in this study are shown and discussed, along with the usefulness of WPPI in different strategies aimed at reducing the release of toxic elements from discarded button cells into the environment.

2. Materials and methods

We studied a total of 64 button batteries from the four most common technologies (alkaline, zinc-air, silver oxide and lithium). One model with maximum consumption was selected from each technology (Linden and Reddy, 2002): LR44 for alkaline batteries; PR44 for zinc-air; SR44W for silver oxide and CR2032 for lithium batteries. Four brands available on the retail market in the EU were purchased for each of these models (Table 1).

We worked with four units of each battery, measuring the quantity of energy they delivered under controlled discharge conditions. We determined the mass — to a precision of 0.1 mg — and the chemical composition of the discharged batteries as they are dumped in the environment, as described below.

2.1. Measurement of stored energy

Stored energy was determined by discharging the batteries under controlled conditions using a metal film resistor with a precision of 1%. The discharge resistance used in each type of battery according to International Standard IEC 60086-2 (IEC, 2006) was 6800 Ω (alkaline and silver oxide), 620 Ω (zinc-air) and 15,000 Ω (lithium). The evolution of the voltage supplied by the battery during the discharge process was monitored using a Fluke logging multimeter, model 287 (intrinsic accuracy of 0.025% and a resolution of 100 μV). The discharge was continued until the residual tension was below 0.200 V. The process took place under laboratory temperature and humidity conditions (22 °C $\pm$ 2 °C and 35% $\pm$ 10%, respectively). To calculate the energy stored in each battery, the experimental discharge curve was integrated between the initial voltage values and the end-point voltage (Table 1) corresponding to each battery type.

2.2. Chemical analysis

A total of 19 elements (Table 2) were analysed, including mercury, lead and cadmium, the three heavy metals of greatest concern according to the regulations on batteries (EC, 2006; USC, 1996). Other major components of some types of batteries such as silver, lithium, manganese, nickel and zinc (Linden and Reddy, 2002) were also determined, in addition to metalloids with recognised toxicity such as arsenic and antimony, which are added to certain metal alloys used in batteries (Linden and Reddy, 2002). The other elements analysed can be found in the different building blocks of the battery — electrodes, separators, electrolyte, container or terminals — either as components or as impurities (Linden and Reddy, 2002). The relative toxicity of the elements was assessed using parameter L (Table 2). Values for parameter L, which denote the highest admissible level of each element for human health, were obtained from three internationally recognised drinking water standards published by the World Health Organization (2011), the US Environmental Protection Agency (2012) and the European Commission (1998). The procedures for assigning parameter L values and calculating WPPI are described in Section 2.3 below.