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Environmental impact of emerging contaminants from battery waste: A mini review

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ABSTRACT

The widespread consumption of electronic devices has made spent batteries an ongoing economic and ecological concern with a compound annual growth rate of up to 8% during 2018, and expected to reach between 18% and 30% to 2030. There is a lack of regulations for the proper storage and management of waste streams that enables their accumulation in open settings and the leakage of hazardous substances into the environment on landfill settings. In addition, recent trends in battery manufacture dictate the use of emerging materials like ionic liquids for electrolytes and nanostructures for cathodes to enhance their energetic properties and lifespan. The full impact of novel battery compounds on the environment is still uncertain and could cause further hindrances in recycling and containment efforts. Currently, only a handful of countries are able to recycle mass-produced lithium batteries, accounting for only 5% of the total waste of the total more than 345,000 tons in 2018. This mini review aims to integrate currently reported and emerging contaminants present on batteries, their potential environmental impact, and current strategies for their detection as evidence for policy and regulation.

1. Introduction

The growth of e-waste streams brought by accelerated consumption trends and shortened device lifespans is poised to become a global-scale environmental issue at a short-term [1], i.e., the electromotive vehicle industry with its projected 6 million sales for 2020 [2,66]. Efforts for the regulation and proper management of electronic residues have had limited impact due to the lack of accountability and low economic viability of recycling facilities [3]. Consequently, a large proportion of electronic equipment is discarded to landfills, where its toxic components are released into the environment [4].

As the main source of electricity for a broad range of devices, batteries are a significant contributor to total generated e-waste [5]. The most used battery types contain considerable quantities of heavy metals like manganese, lead, cadmium, and lithium and other currently identified contaminants widely regarded with high ecotoxicity (Table 1) [6,7]. Furthermore, the small sizes and different compositions between batteries contribute to their improper disposition and make recycling difficult [8].

The demands for ever-increasing efficiency of energy storage systems has led to ongoing research towards emerging materials to enhance their properties [22]; the major trends in new battery composition are listed in Table 2. Among them, nanomaterials are particles or structures comprised of at least one dimension in the size range between 1 and 100 nm [23]. Carbon-based nanomaterials and metal nanostructures are shown to provide higher energetic density, lifespan, and charge efficiency of batteries. As the demand for improved batteries on next-generation commercial applications like electric vehicles increases, nanomaterial production is expected to grow exponentially in the short term at low costs [24].

Several of these novel components are already identified as environmental red flags when issued into different ecosystems; among them are metal oxides [31] graphene materials [14,15] and ionic liquids [18,19]. Nevertheless, the leakage of emerging materials used in battery manufacture is still not thoroughly studied, and the elucidation of pollutive effects in environmental elements such as soil, groundwater, and atmosphere are an ongoing topic of interest for research. When paired with currently reported contaminants, the new generation of

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Table 1
Current and emerging contaminants found on batteries and their ecotoxicological effects.

Contaminant	Ecotoxicological effects	Nanomaterial dimension	References
Cadmium	Intake by ingestion of contaminated food crops. Accumulation in the human body may cause kidney diseases Carcinogenic effects.		[9,10]
Cobalt	Adverse effects on biomass and on physiological activity in crops.		[10]
Copper	Intake by ingestion of contaminated food crops. Liver damage and gastric-related problems. Neurological complications.		[10]
Lead	Intake by ingestion of contaminated food crops. Negative effects on nervous systems, kidney and other organs. Cardiovascular diseases. Carcinogenic effects.		[9,10]
Lithium	Alterations in the development of invertebrates. Interference with nucleic acids synthesis. Accumulation in soil causes severe phytotoxicity.		[11]
Nickel	High oxidative stress in mammalian and terrestrial plant systems. Disruption of ion homeostasis.		[12]
Emerging contaminants			
Carbon-based nanomaterials	Alterations in microbial diversity in soil. Growth inhibition in cyanobacteria and green algae. Bioaccumulation in fish tissues and embryonic development alterations. Activation of local and systemic inflammatory responses.	1 nm single-walled carbon nanotubes. 1–4 nm graphene nanoplatelets. 10–20 nm multi-walled carbon nanotubes. 2–50 nm carbon nanotubes.	[13–16]
Ionic liquids	Antimicrobial activity. Negative impact on plant growth and germination. Bioaccumulation in aquatic ecosystems. High toxicity towards algae.		[17–19]
Metal and metal oxide nanomaterials	Reduced photosynthetic rates and growth inhibition of plants. Modifications on microbial metabolism in soil. High oxidative stress and cell damage.	<50 nm ZnO, Ag and CuO nanoparticles.	[13,20,21]

energy storage devices may prove a challenging case for the proper management of waste streams to minimize ecological impact.

To our knowledge, the present work is the first one to integrate metal nanostructures, carbon-based nanomaterials and ionic liquids in the context of emerging battery materials and their ecotoxicity. Additionally, detection and characterization methods for these species are also listed. However, research on techniques with high specificity in environmental samples remains insufficient for a robust analytical framework to be developed. This mini review should serve as a brief and effective up-to-date outline for further ecotoxicology research on novel battery components and their environmental monitoring.

2. Emerging battery contaminants

2.1. Metal nanostructures

Over the past decade, primary and secondary batteries have migrated from bulk materials into nanostructures derived from transition metal phosphates and metal oxides for their cathode, anode, and electrolyte components. The transition towards emerging trends of manufacture has been driven by the reported enhanced electrical capabilities of developed batteries (higher capacity and throughput and longer lifespan), enabling the consumer adoption of energy storage as a low-cost gateway towards widespread energetic accessibility on communities not connected to the electric distribution grid. The main features, and environmental challenges, of the transition towards emerging manufacturing of batteries are summarized on Fig. 1. Metal nanostructures achieve higher rates of lithium intercalation/deintercalation, and the increased superficial area improves electrolytic contact [32]. The novel features presented by materials technology are translated into increases of the storage capacity and the energetic efficiency of batteries. Currently, these innovations have reached their implementation on vehicles and large-scale storage for domestic settings [33]. The application of metal nanostructures into batteries, from nanoparticles to full-fledged 3D arrays, has also boosted the global demand for the manufacture of nanomaterials based on metals exponentially [24].

The widespread adoption of nanotechnology for emerging batteries can be attributed to the broad range of manufacturing techniques and available materials for nanoparticle production. Nano-compounds derived from metallic oxides such as TiO_2, SnO_2, $Li[MnFe]PO_4$, and Li_2MnO_3 have been explored for enhanced battery components [27,32]. Nanoparticles deriving from metal phosphates such as $LiFePO_4$ are highlighted due to their low-cost application for electrode manufacture, posing better electrochemical stability, lower resistance, and minimizing battery fractures between charging rounds [34]. Nanoparticles, however, exhibit several drawbacks, as they are susceptible to agglomeration due to their high surface area that causes poor contact between consecutive charge/discharge cycles, increasing resistance and reducing capacity [33]. Undesirable surface reactions also reduce the lifespan of nanoparticle-added batteries [31]. These detrimental effects can be minimized by assembling higher-degree (1D, 2D, or 3D) nanostructures that show superior rates of electronic collection and higher capacities [27]. Nevertheless, the manufacturing strategies of complex nanostructures such as hydrothermal synthesis are often difficult and resource demanding, limiting their high-scale manufacture and adoption into commercial products. Materials commonly used for higher-complexity nanostructures include copper nanorods for electrodes, silicone dioxide, and ferro-oxides for nano-porous anodes, and vanadium pentoxide for nanostructured cathodes [33].

Once discarded, recent battery designs may be more prone to puncturing when compared to earlier models due to the lower mechanical integrity of modern casings [31]. Without proper containment, the metal nanostructures contained can then leach into the surrounding soil and water streams. Modelling studies to analyze the extent and pattern of environmental release of metal engineered nanomaterials (Ag-, CeO_2) incorporated into batteries exist, albeit the validation of the results from simulations is often problematic due to the speculative nature of input data [35]. On the other hand, analytical assays have been applied to detect and measure metal oxide nanomaterials on soil and wastewater, typically after pretreatments involving the digestion of samples and aqueous dissolution [36]. Reported strategies to detect and quantify metal nanostructures on soil and water streams include gas chromatography-mass spectrometry (GC-MS) and inductively coupled

Table 2
Main battery types, uses, and trends of manufacturing.

Battery formulation	Applications	Components	Emerging trends	References
Primary batteries				
Alkaline and Manganese–Zinc	- Predominant single-use batteries for household items.	- Zinc as anode. - Manganese dioxide and carbonaceous materials as cathodes. - KOH electrolyte for alkaline and NH_4Cl for Mn–Zn. - Brass current collector for alkaline and graphite for Mn–Zn.	Carbon nanotube cathodes.	[25,26]
Secondary batteries				
Lithium-based (lithium-ion, lithium-polymer)	- Main energy supply in portable consumer electronic products. - Electric vehicles - Military and aerospace	- Graphite as anode. - Lithium nickel, manganese cobalt, $LiFePO_4$ and $LiCoO_2$ as cathode. - Li-Poly includes polyacrylonitrile as a semi-liquid electrolyte. - $LiClO_4$, $LiBF_4$ and $LiPF_6$ as liquid electrolytes for Li-ion.	- Metal and metal oxide nanoparticles ($LiFePO_4$, SnO_2, TiO_2), metal nanostructures (copper nanorods), graphene, CNT and other nanomaterials (silicon nanowires) as electrode components - Ionic liquid doping.	[25,27–30,67]
Nickel-based (Ni–Cd, Ni-MH)	- Biomedical equipment. - Power tools. - Professional cameras. - Mobile phones and laptops. - Electric vehicles.	- Cadmium, iron or metal hydride as anode. - Nickel hydroxide as cathode. - Mixture of KOH, NaOH and LiOH as electrolytic solution.		
Lead-acid	- Automobiles. - Telecommu-nications	- Pb as anode. - PbO_2 as cathode - Sulphuric acid as electrolyte. - Barium sulfate, potassium lignosulfonate and tanning agents as additives		
Silver–Zinc	- Hearing aids. - Wrist watches.	- Zinc as anode - Silver oxide as cathode - Potassium hydroxide as electrolyte.		

plasma-mass spectrometry (ICP-MS) for nanoparticle mass and composition, atomic force microscopy (AFM) for particle size distribution and shape, and Brunauer-Emmett-Teller (BET) technique for surface properties like total area and charge [37].

X-ray absorption spectroscopy (XRS) has also been a valuable tool to elucidate the elemental nature and distribution in soil, water and tissue of potential nano contaminants. Among XRS-based techniques, X-ray absorption near edge structure (XANES) can provide sensible data of the molecular and structural features, composition, morphology and quantity of nano contaminants [38]. This technique has been successfully used to determine the presence of several nanoparticles of Ti, Ag, Au and other metals within food plants such as soybean, maize, barley, and wheat, evidencing the potential introduction of engineered nanoparticles to the food chain through unintended soil uptake [39].

The pollutive consequences of the release of metal batteries at a large scale are not well understood due to the underlying complex interactions with environmental systems [40]. Nevertheless, the effect of metal oxide nanomaterials has been studied on small multicellular and isolated unicellular organisms to elucidate their ecotoxicity. Bozich et al. [41] studied the short- and long-term exposure effects of *Daphnia magna* to lithium nickel manganese cobalt oxide (NMC), a nanoparticulate material commonly used in cathodes. This aquatic organism assimilated large concentrations intracellularly that impaired further nutrient uptake, decreasing reproduction and increasing mortality rates. Toxicity of NMC was attributed to chemical composition of the nanomaterial, however, adhesion to *Daphnia* cells also had a nano-specific condition, indicating that particle size is determinant for cytotoxicity. A similar study was carried out for *Shewanella oneidensis* [42], a soil bacterium. This report concludes that NMC may become a strong source for nickel and cobalt ions, heavy metals that limit bacterial respiration. Both articles agree that efforts shall be taken on product design to substitute toxic elements for more inert solutions as well as incorporate cell surface coatings to reduce nano compound reactivity and release into the environment.

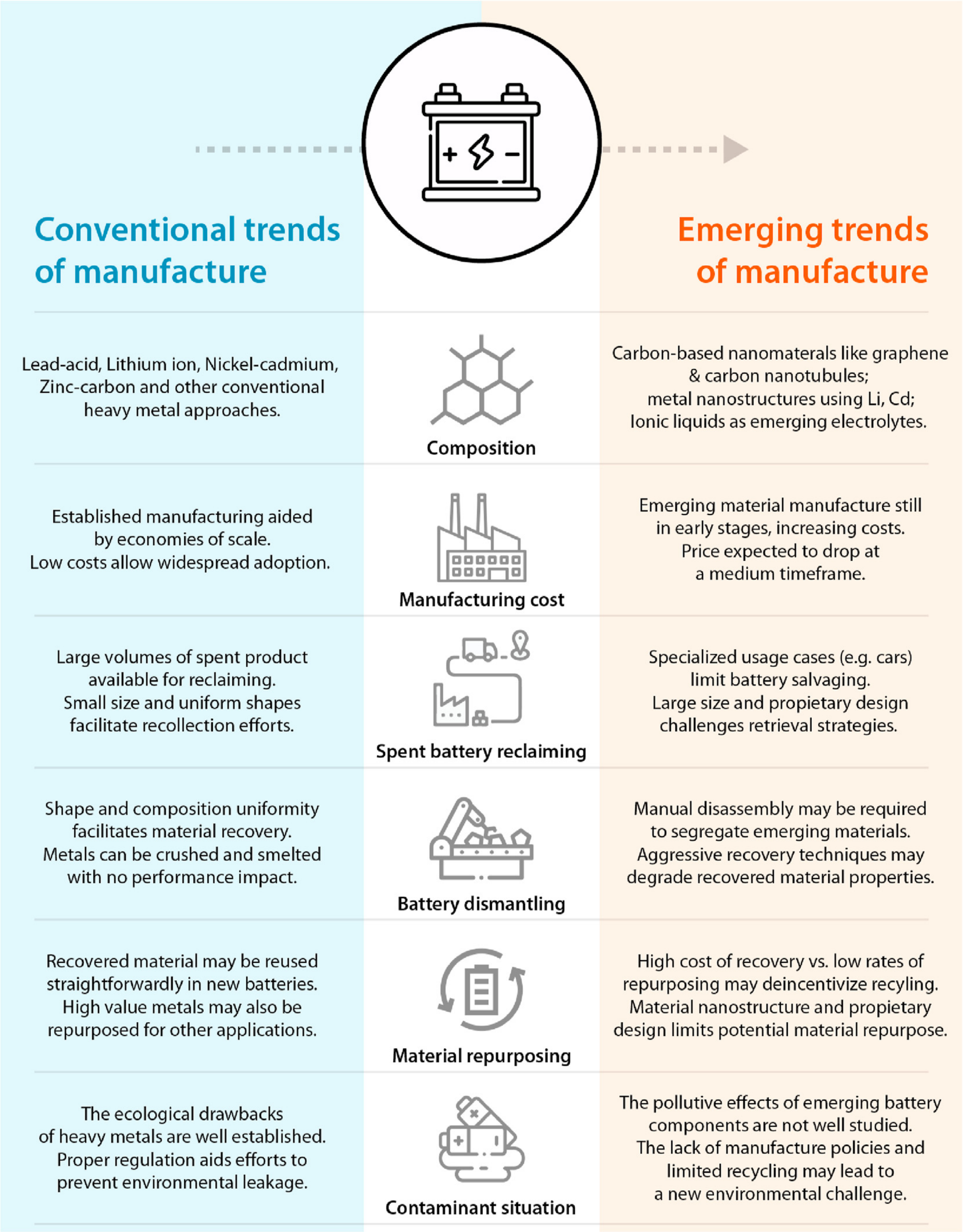
2.2. *Carbon-based materials*

The features of graphene and carbon nanotubes such as high mechanical strength and electric density has established it as a promising replacement of graphite on electrode materials of Li-ion, Zn–C, and other types of batteries [26]. However, the low-cost production of these materials at a large scale has proven to be difficult and processes have struggled to meet global commercial demand that makes the use of these materials widespread [43]. Production strategies like chemical vapor deposition and liquid-phase exfoliation are energy-intensive and overall, environmentally unfriendly due to their usage of large volumes of strong acids and discharge of substantial quantities of CO_2 into the atmosphere [22].

In the context of battery discharge into landfills, graphene can have considerable impact when released into water streams and soils, and its ecotoxicity is dependent on its concentration, molecule nature, particle size, morphology and exposure time [14]. The variable nature of carbon nanostructures makes their identification and quantization on soil and water samples determinant to assess the polluting effect of released nano-waste. Conventional analytical techniques require modification to account for the complex background and low concentrations of tested samples [44]. The application of UV–Vis spectroscopy to quantify graphene-family nanomaterials in natural water samples is highlighted as it is a cheap and straightforward technique widely available in research settings, with minimal sample preparation required [45]. As this study points out, however, the detection of traces of carbon-based materials in environmental samples is still an early endeavor that demands the combination of analytical assays to conclusively eliminate background interference.

As with their inorganic counterparts, XANES can provide valuable information about the structure and chemical features of carbon nanomaterial contamination. In this case, XANES.

Current research on the polluting impact of carbon nanomaterials has



Conventional trends of manufacture		Emerging trends of manufacture
Lead-acid, Lithium ion, Nickel-cadmium, Zinc-carbon and other conventional heavy metal approaches.	**Composition**	Carbon-based nanomaterals like graphene & carbon nanotubules; metal nanostructures using Li, Cd; Ionic liquids as emerging electrolytes.
Established manufacturing aided by economies of scale. Low costs allow widespread adoption.	**Manufacturing cost**	Emerging material manufacture still in early stages, increasing costs. Price expected to drop at a medium timeframe.
Large volumes of spent product available for reclaiming. Small size and uniform shapes facilitate recollection efforts.	**Spent battery reclaiming**	Specialized usage cases (e.g. cars) limit battery salvaging. Large size and propietary design challenges retrieval strategies.
Shape and composition uniformity facilitates material recovery. Metals can be crushed and smelted with no performance impact.	**Battery dismantling**	Manual disassembly may be required to segregate emerging materials. Aggressive recovery techniques may degrade recovered material properties.
Recovered material may be reused straightforwardly in new batteries. High value metals may also be repurposed for other applications.	**Material repurposing**	High cost of recovery vs. low rates of repurposing may deincentivize recyling. Material nanostructure and propietary design limits potential material repurpose.
The ecological drawbacks of heavy metals are well established. Proper regulation aids efforts to prevent environmental leakage.	**Contaminant situation**	The pollutive effects of emerging battery components are not well studied. The lack of manufacture policies and limited recycling may lead to a new environmental challenge.

Fig. 1. Transition of battery manufacture towards emerging materials. Comparison over main features, recycling challenges and environmental considerations. (Illustrations from freepik.com).

developed mainly in water environments, and its complex interaction with full ambient systems is limited due to a lack of controlled conditions. Graphene can be accumulated and has toxicity in unicellular and multicellular organisms and its main mechanisms of damage are divided into physical interaction and generation of reactive oxygen species (ROS) [15]. A knowledge gap exists on the rate of release of novel carbon materials from end-of-life batteries and their uptake, albeit a similar life cycle assessment for the sustainability of super-capacitors that incorporate graphene exists and concludes that graphene is the most impactful component of energy storage waste streams, contributing to 27% higher carcinogenicity in humans and 213% increase in ozone depletion, and thus, recycling of these materials is determinant for the reduction of the environmental impact of manufacturing processes [46].

2.3. *Ionic liquids*

Ionic liquids (ILs) and their blends with metallic compounds have been explored in recent years as promising electrolytes for next-generation energy storage devices. Experimental batteries that incorporate these compounds as electrolytic components display better thermal dynamics that minimizes risks of explosions and simplify charging control systems, lowering costs of manufacture [47]. ILs also display improved electrochemical properties, and intrinsic features like conductivity, viscosity, solubility, and glass transition temperature can be finely tuned by selecting different anionic and cationic combinations through molecular modelling [30]. To this end, prevalent anions (e.g. alkylammonium, imidazolium) and cations (e.g. tetrafluoroborate, bis (fluorosulfonyl) imide) have been used on experimental batteries and super-capacitors with enhanced performance [28].

The fate of ILs when released to the environment is an ongoing concern for research, and the prediction of their environmental impact has been approached mathematically through a model that relies on release patterns, biological activity and degradability [17]. The combination of low volatility and high solubility promotes the accumulation of ionic liquids in soil and water, where they can persist over extended periods [18]. Furthermore, the safety and portrayed 'green' features of ILs have been recently brought to discussion, as current research has linked their potential application to cytotoxic effects on microorganisms like *Escherichia coli and Pichia pastoris,* bioaccumulation on organisms in a higher trophic level, and persistent penetration into agricultural soil [19]. When applied in batteries, compounds that feature pyrrolidinium and imidazolium cations are prevalently used as experimental electrolytes due to improved electrochemical stability [47]. Some derivate salts of these cations have been reported as present in high concentrations at soils located in the vicinity of landfill locations, with promoting effects over mammalian cell apoptosis, and may contribute to the onset of primary biliary cholangitis when combined with other heavy metal pollutants [48]. The analytical quantification on soil extracts near landfills on this study was achieved through thin-layer chromatography, mass spectrometry and nuclear magnetic resonance.

3. Risk assessment and environmental effects of emerging battery contaminants

3.1. Risk assessment of battery nanomaterials

Given the emerging nature of nanomaterials applied for battery enhancement, the characterization of their effects on human health and environment poses unique challenges, as the limited scope of their implementation hampers assessment guidelines of broad relevance [68]. The lack of standardized methods to model nanowaste life-cycle, morphology and particle size distribution also prevents the critical comparison of toxicity effects between nano-scale and bulk materials [49]. The considerable uncertainty of the safe usage of nanomaterials at a wide scale has left a governance gap as the looming large scale adoption outpaces the ability to adjust current regulation according to available studies [69]. The application of risk assessment (RA) for nanomaterials thus takes relevance in the context of battery mass production to support evidence of their safety and bring certainty on the environmental consequences of the disposal of end-of-life products.

Risk assessment refers to the qualitative and quantitative estimation of the negative environmental effect that the exposure to a substance may pose, as well as the socioeconomic consequences of such exposure [70]. Robust RA strategies for nanomaterials must consider an integral characterization of the physicochemical properties of the studied substance as a cornerstone for life cycle hazard modelling. These may include composition, surface morphology, size distribution, chemical reactivity, and agglomeration propensity among others as potential sources of ecotoxicity of the nanomaterial, as the [71]. For currently available assessment strategies, the relevance of each parameter as an attributed hazard source is varied, thus, the specific application of battery nanomaterials' RA remains as a knowledge gap, as disclosure of relevant properties is limited in reviewed articles.

Beyond physicochemical properties, the specific usage case of the studied nanomaterial must be considered to accurately elucidate the fate of the particles over their lifetime. To such an end, the release rate from the source, particle resiliency, and testing of uptake in soil, water, and biological matrixes may be used as a benchmark of waste environmental prevalence. However, in vitro essays usually cannot replicate the material degradation or agglomeration that may result in a non-monitored natural environment and at best material exposure can be roughly calculated, resulting in a misestimation of the risk [50]. In this regard, this review found no study with release kinetics data applicable to the case of battery disposal. Thus, the nanomaterials' fate on this specific instance remains uncertain, raising the need to fill current knowledge gaps before the inclusion of battery nanomaterials becomes broad.

3.2. Environmental impact of battery nanomaterials

The environmental impact of nano-scale materials is assessed in terms of their direct ecotoxicological consequences and their synergistic effect towards bioavailability of other pollutants [51]. As previously pointed out, nanomaterials can induce ROS formation, under abiotic and biotic conditions. When present in biological matrices, it has been widely reported that ROS participate in depletion of reduced glutathione (GSH), lipid peroxidation (LPO) and severe DNA damage. Moreover, nanomaterials are likely to interact directly with biomolecules, such as proteins and carbohydrates, to form protein coronas and other nano-bio complexes; or to participate in biocatalytic processes with adverse outcomes [21].

When entering aquatic ecosystems, nanomaterials might suffer physicochemical alterations, namely in size, aggregation state, and surface modifications. Intake of modified or intact nanomaterials occurs virtually in most trophic levels. Primary producers and microorganisms involved in biogeochemical cycles are prone to membrane damage by oxidative stress in the presence of metal oxides nanoparticles, metal nanoparticles and carbon-based nanomaterials. Nutrient-recycling crustaceans, not only susceptible to oxidative stress, can be affected by the enhanced toxicity of contaminants co-existing with carbon-based nanomaterials [21]. Higher trophic organisms might encounter nanomaterials through direct uptake or through ingestion of algae, filter feeders and benthic organisms. The latter are exposed to nanomaterials because these contaminants tend to aggregate and form sediments [52]. In fish, growth inhibition, hatching delay of embryos and malformations have been observed, as well as histopathology damage [14].

The transformation mechanisms and toxicity of engineered nanomaterials in atmospheric, terrestrial and aquatic compartments have been reported [23]. Among these, the nanomaterials released to the atmosphere bind to atmospheric particulate matter (PM), and could have a negative impact on climate and human health [53]. Several morphological and physiological aspects of soil bacteria and fungi, such as cell membrane/wall, cellular density and metabolism are directly affected by long exposures to nanomaterials. Similar molecular effects have been observed in different plant species (*Arabidopsis thaliana, Nicotiana tabacum, etc.)*, as well as geno-toxic effects from chromosomal aberration and cell cycle alterations [54].

Full characterization of nanomaterials and their aggregates is required as a starting point for their eco-toxicity assessment. Secondly, complexity in their interactions increases due to biotic and abiotic modifications when introduced to the environment. Furthermore, focus on transfer of nanomaterials from primary producers, to higher trophic levels and potential ripple effects must be considered to fully understand their environmental fate [55].

4. Regulatory and recycling challenges of emerging batteries

The regulatory action of the USA, Germany, Japan and China on spent batteries is summarized by Fan et al. [56]. Most of these policies are constrained to the responsibility of the manufacturer and the recycling companies but omit the consumer's. Additionally, in the case of the USA framework, recycling policies are not unified at the state level. On the other hand, it was not until the year 2020, that the European Commission proposed a Batteries Regulation which, unlike the Batteries Directive that its repealing, is binding on all EU countries, thus promoting an even regulatory implementation. A common practice in the waste industry of developed countries is to export the collected, sometimes dismantled, spent battery components to developing countries, for processing and landfilling. Regulation in the receiving parties is often more permissive or ambiguous in the delegation of responsibilities [57,58].

The environmental impact of battery emerging contaminants has not yet been thoroughly explored by research. Parallel to the challenging regulatory landscape of battery recycling, the lack of adequate nanomaterial risk assessment has impaired the regulation of their inclusion at a product level. Nanomaterial governance has been hindered by the lack of analytical tools required to assess potential benefits and liabilities of emerging products and waste resulting from improper disposal. As such, the development of analytical tools and risk assessment frameworks remains an ongoing interest of governing bodies such as the European Commission, requiring the development of comparative and flexible approaches to study nanomaterial safety, cost-benefit estimation, and social impact [49]. Furthermore, for risk assessment to become an integral part of nanomaterial regulation, it must develop from the case-by-case scenario towards consented cut-off values and efficient grouping the potential effects of nanowaste according to their general morphology and release behavior [50]. Finally, research on the long-term release and organic intake models of nanowaste are expected to have added value for decision taking due to the complexity of their study and the broadness of their scope [50,59]. Management policies for nano-waste are also limited as current regulations only specify these materials' disposal requirements to those that apply for the products that contain them and not as a specific waste stream [3].

Emergent materials pose new challenges to the already complicated issue of battery recycling. Albeit there is an environmental incentive, the economic viability of treating and recycling battery waste remains a two-pronged issue: first, the current salvaging infrastructure is mainly designed to process legacy technology and not recent trends of manufacture, limiting the recovery of materials to those present in large quantities (e.g., heavy metals) and excluding nanomaterials and novel electrolytes, albeit their higher cost of fabrication [24]. Moreover, the high variability of battery shapes, sizes, and compositions demand additional sorting steps and the combination of reclaiming strategies to increase recovery yields for the full waste stream [24,60].

Conventional solutions for recycling of batteries include hydrometallurgy and pyrometallurgy. These operations result in high yields but require large amounts of chemical reagents and high energy input, respectively [9]. The ongoing research focuses on profitable and environmentally safer recovery methods, such as biologically-assisted methods [61] and other promising chemical and physical techniques [62]. Research on recapturing nanoengineered materials from battery waste is limited [24]. The experiments on retrieval of carbon nanotubes from lithium ion batteries are also part of this short list of attempts [63]. Even fewer remediation approaches have been studied using jellyfish secreted mucus to trap gold and quantum dots nanoparticles in an aqueous environment [64]. Other gel-like substances like Poly(-*N*-isopropyl acrylamide) have also been tested for decontamination of water from gold nanoparticles [65].

As the second issue, the reinsertion of recovered products into the market is impaired by their highly specialized nature, limiting their applicability. Usability is furtherly challenged as the extreme conditions of recycling strategies may degrade the salvaged materials [24]. The added effect of these drawbacks makes the modernization of battery recycling not attractive to the market. Thus, the destination of a high proportion of new energy storage devices are landfills, where their components leach out into soil and water, and if the litter is incinerated, the atmosphere [37].

Further characterization of the release and the effects of exposure of these novel compounds from batteries is required to understand the full extent of pollution by emerging contaminants and issue proper regulation frameworks to limit improper e-waste disposal. Adaptation of current approaches on waste management can secure the environment from being polluted and provide new recycling strategies of scarce materials. New ways of recycling emerging technologies used on batteries is an opportunity to grow and release the ecological concerns of novel materials to be applied on energy storage. Adequate recovery of essential materials can become an alternative to natural resources exploitation.

5. Conclusions

This review briefly summarizes the main emerging materials reported to enhance battery performance and their potential environmental impact towards the onset of large-scale manufacturing. The demand of energy storage devices is expected to surge as the electronic mobile device market grows and the efforts for the electrification of the global vehicle fleet succeed. This surge is however not coupled with proper regulation efforts globally, resulting in improper production and disposal practices that expose potential hazardous substances to the environment.

The ever-looming increase in e-waste demands a higher attention to the detection and quantification of potential contaminants and their disruptive effects. For batteries, a number of pollutive agents has been already identified on consolidated manufacturing trends, including lead, cadmium, lithium, and other heavy metals. Moreover, the emerging materials used in battery assembly may pose new concerns on environmental safety as the reports on their toxic effects remain ambiguous. Reviewed articles already document the presence of carbon and metal nanostructures in landfill settings, albeit measurement is often difficult due to the limits of detection and quantification of used techniques. In order to generate evidence for decision and policy making, more effective detection methods are needed for nanostructured materials and ionic liquids used in batteries, preferably designed for a field setting.

The disposal, reclaiming and repurposing of energy storage devices remains a challenge, as the majority of consumer-grade batteries at the end of life are sent to landfills, where their components leach into the soil and water basins. The proposed emerging materials add a layer of complexity on this issue, as their recovery is often costly and their specialized composition often limits their applicability in other fields. Current recycling facilities are limited for the salvaging of nanostructures and ionic liquids; when coupled with the absence of regulations, these emerging materials may pose a new environmental threat. Manufacturers that migrate towards the new generation of battery materials shall ponder the alleged improved energetic performance that their inclusion has with the potentially environmental or financial costs that their handling, or lack thereof, has at end-of-life.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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