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Perspective

Upcycling Metal(loid) Contaminants to Produce Critical Raw Materials: The Nexus of Water Treatment and Material Criticality

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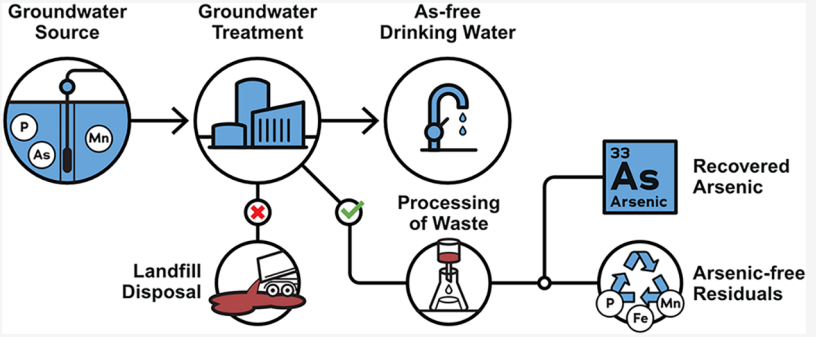

ABSTRACT: The Critical Raw Materials Act adopted by the European Commission in 2024 signals a growing shift in the societal value of many elements, which has important implications for the water treatment sector. This legislation partly aims to increase production of Critical Raw Materials (CRMs) from waste streams, with many CRMs being elements with which the water sector has decades of experience, such as the notorious contaminant and newly classified CRM, arsenic. In this *Perspective*, we use arsenic as a case study to explore how water treatment waste can be repurposed to contribute to CRM supply chain requirements. Combining arsenic mass balances for indicative groundwater treatment plants and EU statistics of water use and arsenic compound consumption, we propose that arsenic upcycling integrated with water treatment can help offset imports of arsenic compounds. However, research is now needed to develop more holistic treatment systems that integrate CRM upcycling with contaminant removal and to better understand the political, institutional, and social drivers that can accelerate adoption of such systems at water utilities. With this work, we intend to stimulate a discussion of water treatment as a discipline that can both improve water quality by removing metal(loid) contaminants and generate local sources of CRMs.

KEYWORDS: *Critical Raw Material (CRM), Water treatment, Arsenic, Upcycling, Circular economy, Groundwater, Resource recovery*

1. CRITICAL RAW MATERIALS ACT

In March 2024, the European Union (EU) adopted the Critical Raw Materials Act,[1] a landmark piece of legislation with important consequences for the water treatment field. This act aims to secure sustainable local sources of Critical Raw Materials (CRMs) needed for the "net zero industry, the digital industry, aerospace, and defense sectors",[2] with specific support for CRM production from secondary materials (i.e., wastes). This act applies to the >30 CRMs classified by the EU (Figure 1), as well as the EU's Strategic Raw Materials (we herein refer to both Critical and Strategic Raw Materials as CRMs for brevity). The designation of CRM is based on (1) the material's critical supply risk and economic importance and (2) the material's indispensable application across the above-mentioned strategic sectors.[3] While explicit legislation on CRM production is unique to the EU, many other regions have defined similar lists of CRMs depending on domestic inventories of material resources and estimates of future consumption, including the United States (US),[4] Canada,[5] South Africa,[6] and India.[7]

As such, experts in the water treatment field must not ignore the opportunity to consider viable value-adding possibilities now afforded by the intense focus on local economies and domestic production of critical materials. Many materials presently classified as CRMs around the world are also environmental contaminants, which require costly removal. In particular, arsenic has been identified as a CRM by governmental agencies in several regions, including the EU and US,[3,8] due partly to the use of metallic arsenic (As(0)) in

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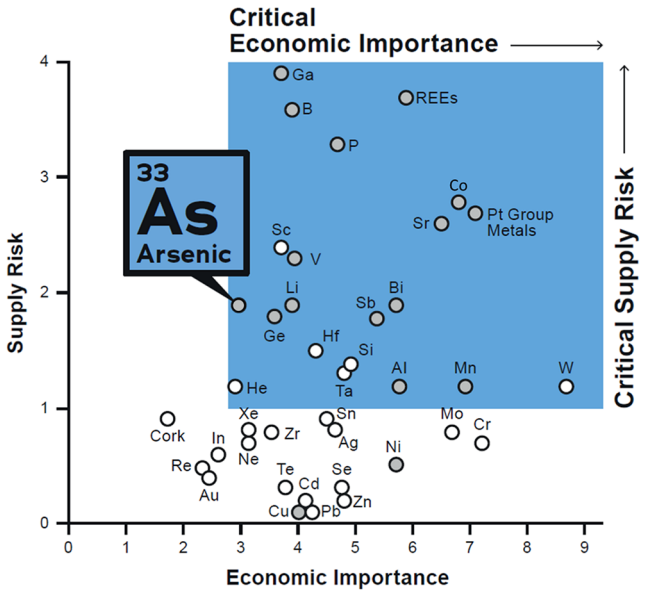

Figure 1. Supply Risk and Economic Importance for selected materials based on European Commission definitions (formulas to calculate Supply Risk and Economic Importance can be found in European Commission, 2023).[3] Critical Raw Materials (CRMs) are given in the upper right quadrant (blue area). Nickel (Ni) and copper (Cu) are classified as strategic raw materials (SRMs) in the EU. Filled symbols indicate materials classified as CRMs or SRMs in both the EU and US. Several CRMs have water treatment relevance, including arsenic (As), antimony (Sb), phosphorus (P), manganese (Mn), vanadium (V), Ni, and Cu.

batteries, alloys, and high-speed electronics (e.g., semiconductors).[9] Arsenic is an infamous naturally occurring carcinogenic water contaminant that has been on the forefront of water research for years. Other notable CRMs that have legacies as water contaminants include manganese, copper, nickel, antimony, and vanadium.[10−13] The current best available technologies for removing these contaminants may shift as the waste produced becomes a potential source of profit.

The dual role of an element as both a contaminant and a valuable resource, and its effect on water treatment research, may be best exemplified in the history of phosphorus management.[14] The eutrophication of surface water from excess phosphorus discharge combined with the need for sustainable sources of phosphorus-based fertilizers resulted in sewage sludge treatment having a profitable phosphorus compound coproduct. This has sparked a transition in the municipal wastewater sector wherein municipal wastewater treatment plants are being rebranded as wastewater resource recovery facilities, with a primary focus on nutrients.[15,16] Although phosphorus derived from mining remains inexpensive compared to the costs of recovering phosphorus from wastewater, wastewater treatment is often integrated with phosphorus recovery for cobenefits extending beyond economics, such as pollution prevention, resource conservation and compliance with local regulations. The challenge signaled by the Critical Raw Materials Act of creating local sources of CRMs from other elements with contaminant and commodity properties requires an analogous renaissance of the broader water treatment field to identify, develop, and adopt holistic approaches that integrate treatment and upcycling. Generating valuable CRMs from metal(loid) contaminants would not only decrease CRM import reliance, but could allow for more effective best available water treatment technologies, and could decrease the impacts of contaminant-laden waste disposal, which for arsenic, can be one of the highest costs associated with routine treatment plant operation.[17,18]

In this *Perspective*, we explore the potential for water treatment, when integrated with upcycling methods, to contribute to the supply chain requirements of arsenic. Our goal is to stimulate a discussion of the potential role water treatment may play in CRM supply chains and to identify key requisite research gaps. We hope to begin to reshape the narrative of the broader water treatment discipline from one that primarily aims to remove contaminants to one that can be

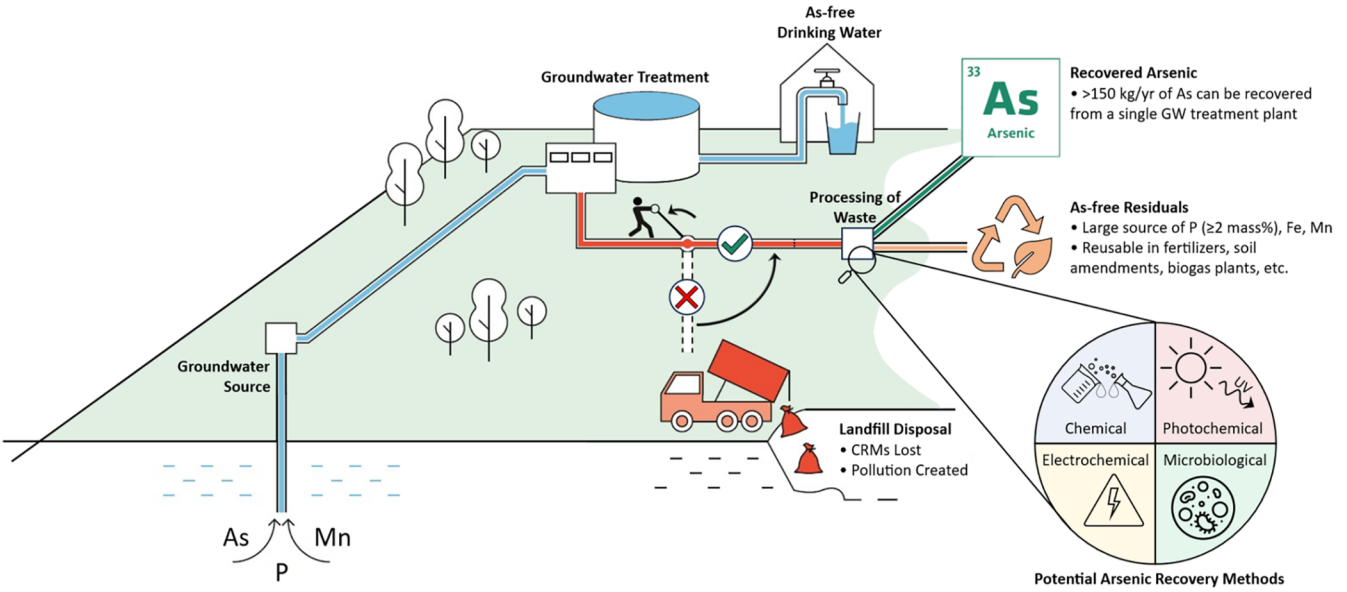

Figure 2. Schematic of groundwater treatment and arsenic upcycling wherein waste produced from treatment is diverted from landfill disposal and processed to yield As(0) and other CRMs.

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designed to improve water quality while creating local sources of CRMs (Figure 2).

2. ARSENIC COMPOUND PRODUCTION AND SUPPLY

Knowledge of current CRM production and supply statistics is a prerequisite to assess the extent that CRMs derived from water treatment can contribute to local demands. For arsenic, as with many CRMs, the majority of global supplies are generated from direct concentration of mined ore or from the byproduct slag produced during ore refining. While arsenic mineral reserves are generally secure (20 times world consumption),[8] these mineral deposits are not distributed evenly, creating strong reliance on imports. Furthermore, the production of valuable arsenic compounds, such as As(0), via mining and concentrate processing leads to profound environmental degradation,[19,20] highlighting a secondary benefit of domestic production of arsenic compounds via waste upcycling. With respect to arsenic supply and consumption, it is first important to note that not all arsenic compounds are CRMs with established markets and continent-wide trade tracked in the EU. Indeed, metallic As(0) is the only arsenic compound with a Eurostat Combined Nomenclature (CN) trade code, consistent with its economic importance and its growing use in several industries, including electronics, metallurgy and chemicals. Therefore, upcycling methods should aim to convert the forms of arsenic often found in water treatment waste [e.g., arsenite (As(III)) and arsenate (As(V))] to metallic As(0) to be most beneficial. From 2016 to 2020, the EU imported an average of 500 tons/year of metallic As(0) to help meet its annual consumption of 1260 tons/year. Over 90% of the 500 tons of imported As(0) was provided by a single country, China.[21] The amount of As(0) exported from China to the EU is also similar to Chinese exports of As(0) (700 tons/year) to the US, where domestic As(0) production is not currently practiced despite its CRM classification.[8] Therefore, the development of just 100 tons/year of arsenic removed from groundwater and converted to As(0) would have a major impact on import decisions for both the US and the EU. However, since <1% (i.e., < 13 tons/year) of As(0) consumed in the EU is currently sourced from secondary materials or recycling, offsetting a meaningful fraction of As(0) imports will likely require significant investment.[21]

3. STRATEGIC WATER BODIES FOR ARSENIC UPCYCLING

Water bodies contaminated with elements classified as CRMs are ideal opportunities for the 2-for-1 benefit of treatment and upcycling. Water bodies that have been traditionally investigated for CRM treatment and recovery include municipal wastewater as a source of phosphorus[15] and geothermal brine as a source of lithium and other metals.[22] For arsenic, which has been the focus of much less upcycling research than other CRMs, these water bodies are not applicable due to their typically low arsenic content. Rather, groundwater and mining-impacted aquatic systems represent two possible upcycling opportunities that have unique chemical compositions and that are already typically targeted for treatment to minimize aqueous arsenic in drinking water[23] and mining wastewater effluent.[24] In this section, we briefly introduce water bodies contaminated with arsenic that can be targets for treatment and waste upcycling to replace current treatment waste management practices.

3.1. Groundwater. Geogenic arsenic in groundwater remains a global health threat. Hundreds of millions of people are estimated to be exposed to arsenic levels in drinking water above the 10 μg/L World Health Organization provisional limit.[25] Furthermore, the financial burden on stakeholders that rely on groundwater that is out of compliance can be catastrophic.[26] Although many arsenic treatment methods for groundwater and surface water have been proposed, arsenic sorption to iron (oxyhydr)oxides is by far the most common strategy in large-scale conventional treatment and small-scale decentralized systems.[27,28] Iron-based treatment removes arsenic effectively, but generates large quantities of treatment sludge that must be managed appropriately. This sludge can contain high arsenic contents (>2000 mg As/kg), even though arsenic levels in groundwater can be relatively low (i.e., 10−500 μg/L).[17] Furthermore, due to the often order-of-magnitude higher phosphorus content than arsenic in groundwater,[29] phosphorus levels in this sludge can exceed 20 g/kg. Despite the multiple CRMs typically contained in groundwater treatment waste, this sludge is largely regarded by the water treatment sector as a disposal problem, rather than a revenue opportunity. The current linear economic view of arsenic-rich sludge being waste (and not a recoverable resource) is evident from the fact that landfilling is the most common disposal method in high-income areas,[30] which leads to the loss of CRMs contained in the sludge (Figure 2). In areas without the space and resources for landfilling, alternative disposal strategies that lead to the same loss of CRMs are common, such as solidification and stabilization in construction materials (i.e., bricks, concrete), discharge to sewers and simple open disposal to surface water and soils.[18]

3.2. Mining-Impacted Waters. Although arsenic-laden sludge from groundwater treatment is a particularly important target for upcycling research because it is an unavoidable byproduct of providing safe drinking water, mining-impacted waters can be a major supplemental source of upcyclable arsenic. Mining activities can generate two key water sources containing intense concentrations of arsenic and other metal(loid) CRMs. First, the oxidative weathering of arsenic-bearing sulfide minerals in waste rock and tailings of abandoned or closed mine sites leads to acidic leachate (i.e., acid mine drainage, AMD) with aqueous arsenic and antimony concentrations that can exceed 10,000 μg/L.[31] We also note that the solid tailings themselves can have high resource recovery potential. Second, purifying mineral ore to produce metals such as copper or gold can generate wastewater containing concentrated levels of arsenic and antimony (i.e., >1000 μg/L) that were present as impurities in the original mineral (e.g., arsenic or antimony-rich pyrite).[32,33] This wastewater can decimate adjacent aquatic ecosystems if released without treatment.[34] A recent example of an environmental disaster caused by such wastewater occurred near Kitwe, Zambia, where millions of liters of metal(loid)-laden copper mining wastewater entered a tributary of the Kafue River, leading to extensive ecological damage, including mass fish die-offs and destruction of crops along the riverbanks.[35] Notably, the environmental impacts of these mining activities can remain for decades after closure of the mine and end of mineral processing, leaving a steady supply of aqueous arsenic and antimony for treatment and upcycling.[36] Several treatment methods have been documented to

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remediate arsenic-bearing AMD and metal processing wastewaters, with different methods excelling in different conditions. For example, AMD contamination that is dispersed over larger areas has been targeted by microbiological sulfate reduction to form solid arsenic-sulfides,[37] phytoremediation with arsenic hyperaccumulating ferns or by surface complexation to Fe(III) (oxyhydr)oxides generated by Fe salt addition.[38] Conventional water treatment methods can be applied to the localized arsenic-bearing wastewater produced from metal refining, such as ion exchange, reverse osmosis or Fe(III) precipitation.[34] However, regardless of the remediation strategy, each method generates waste that must be managed (e.g., hyperaccumulating ferns are harvested and incinerated, with arsenic-rich ash disposed via landfill).[39] Similar to sludge generated during groundwater treatment, the upcycling of arsenic following treatment of mining-impacted waters is almost never considered,[40] with waste stabilization or landfilling being the most common practice.

4. ARSENIC WASTE PRODUCTION AT SELECTED TREATMENT PLANTS AND THE POTENTIAL TO CONTRIBUTE TO LOCAL CRM SUPPLIES

Accurately quantifying the total amount of arsenic that can be upcycled from groundwater treatment sludge on a continent scale is challenging partly because it depends on several parameters, including groundwater treatment performance, for which continent-wide databases are not available. Since accurately estimating the upcyclable arsenic quantity from treatment waste across the EU is not possible with current databases, investigating arsenic mass balances at indicative groundwater treatment facilities with published statistics on plant capacity, average arsenic fluxes and sludge composition can serve as useful illustrative examples. As a first example, we consider the Water Production Center (WPC) Mol (Belgium), which produces drinking water from groundwater treatment. This plant has a capacity of 3,650,000 m^3/year, with influent arsenic concentrations ranging from 31 to 50 μg/L (average 41.5 μg/L) and treated water concentrations <5 μg/L (average 0.4 μg/L).[17] Therefore, this plant has the capacity to produce between 95 and 164 kg/year of arsenic contained in the treatment sludge, with an average of 150 kg/year (0.15 tons/year). We note that these values should be regarded as indicative rather than exact because treatment performance and plant operation, including total annual treated volume, can vary from year to year. Considering that groundwater accounts for 65% of drinking water in the EU (population of ∼450,000,000) and that per capita water supply to households is 52.5 m^3/year, approximately 4200 groundwater treatment plants the size of WPC Mol would be required to meet EU drinking water needs. This number of plants would generate enough arsenic contained in treatment waste to exceed the total import supply of As(0) to the EU if each plant had identical properties as WPC Mol and if 100% of arsenic contained in the waste was converted to As(0), which are obvious assumptions. However, groundwater treatment in the EU is not limited to drinking water production (households account for only 12% of water use). As a second example, the Triglia treatment plant in Northern Greece is a full-scale groundwater treatment plant and sole source of agricultural water in the region. This plant has a capacity of 875,000 m^3/year with an average influent of ∼200 μg/L arsenic.[41] Therefore, the Triglia plant has the capacity to yield 170 kg/year (0.17 t/year) of arsenic contained in the treatment sludge.

These groundwater treatment examples highlight both the potential for arsenic treatment and upcycling to contribute to domestic As(0) supplies, consistent with the Critical Raw Materials Act, as well as the challenge due to the need for infrastructure and adoption in the sector. However, arsenic present in mining-impacted waters might have an even higher upcycling potential by mass. One recent estimate of the total arsenic flux through a river contaminated by legacy mining activities (Carnon River, U.K.) suggests 2.2−4.2 tons/year of arsenic is transported to the river estuary, despite the cessation of mining activities decades ago.[42] We acknowledge, however, that the comparison between the groundwater and mining-impacted surface water examples are not identical since the mining-impacted system requires the implementation of treatment infrastructure that is not yet in place, in contrast to existing groundwater treatment plants that could be retrofitted. While the purpose of this *Perspective* is not to perform a comprehensive budget of arsenic mass in all groundwater and mining-impacted waters in the EU, the aforementioned treatment plants serve as illustrative examples of how arsenic treatment and valorization of arsenic-laden waste can contribute to local As(0) supplies. Further research is now needed to quantify arsenic-laden waste production on continental scales to more accurately identify the extent to which As(0) production from groundwater treatment waste can offset As(0) imports.

5. POSSIBLE ARSENIC UPCYCLING STRATEGIES

Several potential technical approaches for arsenic upcycling have promise. The first group of methods is based on reduction of arsenic separated from the treatment waste to form As(0). The initial separation step can be performed by adding strong base to mobilize negatively charged arsenic bound to the iron oxide matrix[43] or by dissolving the arsenic-bearing waste via Fe(III) reduction, the addition of chelators or strong acid.[44] The subsequent transformation of mobilized aqueous arsenic to As(0) can be facilitated by chemical addition[45,46] or by photochemical techniques, such as UV/TiO_2[47] or UV/formic acid processes.[48] Electrochemical methods can also reductively transform aqueous arsenic to As(0)[49] and have the unique property that they can be operated without a continuous supply of chemicals.[50]

Another potential upcycling strategy is based on microbiological biovolatilization of gaseous (methyl)arsine species (hereafter referred to as arsines). In this strategy, specific strains of bacteria are exploited to convert inorganic arsenite or arsenate to volatile arsine species via enzymatic arsenic methylation, which is thought to be the rate limiting step,[51] followed by reduction to arsines. Several bacterial strains have been reported to efficiently biovolatilize arsines (e.g., *Arsenicibacter rosenii*), with strains that effectively methylate arsenic typically showing the highest biovolatilization rates.[52] Genetically engineering microorganisms to improve methylation rates, which is an active area of research, has also been shown to enhance overall production of arsines.[53] Biovolatilization is attractive not only because it can readily separate arsenic (and other CRMs, including antimony) from a mixture of nonvolatile components, but also because the products of biovolatilization, such as trimethylarsine,[54] can be the same species of arsenic used to directly synthesize semiconductors (e.g., via chemical vapor deposition).[55]

From an infrastructure perspective, traditionally, water treatment techniques are performed in series. Therefore,

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retrofitting a modular section that specifically upcycles arsenic (using one of the above methods) into an existing treatment system is theoretically possible, though the size specifications would depend on each location. Separation of a mixed metalloid-sludge could be done on-site, or in a centralized manner at larger regional separation plants. Once separated by element, sale and (re)use can occur. Critically, any upcycled arsenic products must meet industry specifications, which vary by application. For example, metallurgical processes involving As(0) may tolerate lower-grade purities, whereas advanced electronic materials require higher purities. Further research is therefore needed to ensure that upcycling methods achieve efficient separation while also delivering products that meet end-use requirements.

While the methods outlined in this section represent promising strategies for upcycling arsenic-laden groundwater treatment waste, they remain at an early stage of development, with limited documentation in the scientific literature and, to our knowledge, no current implementation in real-world systems. Therefore, robust data sets needed to perform comprehensive techno-economic analyses, life cycle assessments, or feasibility studies are lacking. Improving the likelihood of adoption of upcycling methods therefore requires additional targeted research to refine the underlying chemical processes that govern arsenic upcycling and to generate the data necessary for evaluating their economic viability and environmental sustainability.

6. BENEFITS AND CHALLENGES OF UPCYCLING WATER TREATMENT WASTE

The removal and subsequent upcycling of arsenic from contaminated waters has several key societal and environmental benefits. First, generation of valuable CRMs from waste can decrease the reliance on imports of CRMs from third-party countries and lead to lower risks of CRM supply disruptions. For arsenic, local production of As(0) is particularly relevant because traditional methods of obtaining As(0) via mining and concentrate processing severely degrade the environment and lead to hot-spots of extreme soil and water contamination near the sites of mineral excavation and processing.[20] Second, arsenic upcycling represents an improved strategy to manage toxic arsenic-laden water treatment waste, which is universally viewed as a disposal issue by the water sector. All current disposal practices, such as landfilling, stabilization in building materials, sewer discharge and open disposal, are unsustainable and ultimately result in unacceptable emissions of arsenic to the environment as well as the loss of other valuable resources (e.g., phosphorus, manganese).[17,30] Since appropriate disposal of this waste is already one of the highest operating costs for treatment plants,[56] redirecting these expenditures to sludge upcycling can also help improve the financial sustainability of this approach. Third, the production of valuable materials from arsenic-laden waste can potentially offset the financial costs of water treatment. The financial benefits of arsenic upcycling might be further improved by subsequent research investigating the production of high-value arsenic-bearing materials from upcycled As(0) precursors, particularly semiconductors, such as the 2-dimensional form of pure As(0), arsenene.[9] However, even if arsenic upcycling does not result in a substantial profit stream from the recovered materials alone, this approach can still be a unique opportunity for companies with core business activities in arsenic products to increase and brand their social impact by switching to a more sustainable arsenic source derived from improving water quality.

Despite these benefits, arsenic upcycling is not without some societal and technical challenges. Since chronic arsenic consumption was first linked to cancer decades ago,[57] arsenic has elicited a profoundly negative image in the minds of scientists, practitioners and the general public. The shadow of arsenic toxicity looms large over its expanding and less widely appreciated application in essential products for many strategic industries (e.g., high-speed electronics), which might hinder the adoption of new sludge management practices in the water sector. However, the European Commission's Critical Raw Materials Act and the recent classification of arsenic as a CRM in the EU and US can catalyze a renaissance in the scientific and public perception of arsenic. Second, there can be a misconception by water treatment practitioners about the quantity of arsenic contained in treatment waste. A recent publication showed that the arsenic content in treatment waste can be decoupled from the arsenic groundwater concentration, with high reported arsenic waste mass fractions (1000−2000 mg As/kg) found in the sludge of treatment plants with low influent arsenic levels (1.1−25 μg/L).[17] Consequently, it can be incorrect to assume that treatment waste contains negligible arsenic levels simply because the groundwater arsenic concentrations are below 10 μg/L. Finally, current regulatory frameworks for managing arsenic-laden groundwater treatment waste do not provide incentives for waste upcycling, likely due to the absence of mature technical methods that can transform such waste into As(0), one of the most valuable forms of arsenic. However, the widespread implementation of phosphorus recovery in wastewater treatment plants shows how regulatory guidance can accelerate adoption of recovery methods even in the absence of strong economic drivers, which is essential for encouraging novel technology adoption in a sector known for institutional resistance and high sensitivity to social acceptance.

From a technical perspective, one of the barriers that can prevent the adoption of arsenic upcycling is that arsenic-bearing wastes are typically heterogeneous and can contain metal(loid)s that might interfere with upcycling efficiency. This challenge is exemplified by co-occurring arsenic and phosphorus in groundwater and arsenic and antimony in mining-impacted waters. It is well understood that arsenate (As(V)), the oxidized form of arsenic, shares similar chemical reactivity with phosphate and antimonate (Sb(V)), the oxidized form of antimony. The similar chemical properties of AsO_4, PO_4 and SbO_6 oxyanions (e.g., sorption reactivity, pH-dependent charge) can make separation difficult, but not impossible. In particular, the different reduction potentials of each species can be leveraged to selectively convert arsenic extracted from the bulk waste to solid As(0) or volatile (methyl)arsines, leaving a more easily refinable waste for subsequent phosphorus or antimony recovery.

Finally, the underlying costs of engineering interventions introduce new financial risks that must be considered by treatment plant operators and others engaged in the water sector. Although the costs of converting arsenic-laden groundwater treatment waste to form As(0) are difficult to estimate accurately due to the immaturity of this approach, it is nevertheless possible that the sale of upcycled As(0) can help offset the costs of implementing upcycling methods. Targeted research into new chemical, electrochemical or biological upcycling methods, including energy and reagent require-

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ments, conversion efficiencies, and the behavior of co-occurring elements (e.g., phosphorus) would yield important data to more reliably assess the economic and environmental benefits of arsenic-laden waste upcycling. The legislative push from the Critical Raw Materials Act in the EU provides a new impetus to re-envision how upcycling water treatment waste can contribute to circular economy strategies for CRMs. This *Perspective* highlights potential pathways for the socially-, environmentally-, and economically sustainable management of waste generated in water treatment and is intended to motivate further research into the feasibility of converting contaminants into valuable CRMs.

7. A NEW VIEW OF TREATMENT: INTEGRATING METAL(LOID) CONTAMINANT REMOVAL WITH CRM UPCYCLING

One of the most impactful opportunities created by arsenic upcycling is the potential to redefine the role of water treatment. As research on arsenic upcycling builds, we can use new knowledge to design innovative treatment systems that aim not only to remove arsenic to below local limits (i.e., the traditional role of water treatment), but also to create treatment end-products that are more easily converted to valuable materials. For example, this kind of integrated treatment would seek to maximize the arsenic mass fraction of treatment end-products, which facilitates arsenic upcycling,[46] while minimizing the formation of solids that interfere with recovery, such as calcite ($CaCO_3$). In one of our recent articles in *Environmental Science & Technology*,[43] we showed that calcite present in arsenic-laden iron oxide groundwater treatment sludge substantially inhibited the extraction of aqueous arsenic from the sludge, which is a key initial step for upcycling. Calcite can form during aeration of groundwater, which increases pH due to CO_2 degassing, leading to conditions that promote calcite precipitation, especially for groundwaters supersaturated with respect to calcite.[58,59] Based on this information, one method to generate solid treatment end-products with properties that favor As(0) formation would be to oxidize anoxic groundwater via hydrogen peroxide dosing, rather than aeration.[60] Anoxic H_2O_2 dosing would limit CO_2 degassing and thus calcite formation and is more effective than aeration alone at co-oxidizing Fe(II) and As(III) to form Fe(III) and readily sorbed As(V), which enhances the arsenic mass fraction in the sludge.[60] Modifying groundwater treatment to incorporate H_2O_2 oxidation rather than aeration is just one scenario where research on arsenic upcycling can guide the design of water treatment plants to encompass the new dual role of provider of clean water and local sources of CRMs. Continued research into coordinated treatment and metal(loid) upcycling will no doubt bring further innovations that can be implemented widely to lessen the need for unsustainable waste management practices and decrease the supply risks of CRMs.

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Notes

The authors declare no competing financial interest.

Biography

Case van Genuchten received his PhD in 2013 from the Environmental Engineering Department at the University of California, Berkeley (USA), where he focused on developing decentralized arsenic treatment methods for rural areas of India and Bangladesh. He has continued to work on arsenic treatment methods applied in low- and high-income countries since his PhD, including as a postdoc at the University of Lausanne (CH) and as a Veni grant fellow at Utrecht University (NL). His recent research aims to develop new methods to valorize the waste produced from water treatment, yielding Critical Raw Materials and other high-value products. He is particularly interested in applying synchrotron-based characterization techniques to understand the molecular-scale reactions underpinning water treatment and waste upcycling technologies, which was recognized by the 2020 Farrel W. Lytle Award from the Stanford Synchrotron Radiation Lightsource (SSRL). Case is currently a Senior Researcher in the Geochemistry Department of Geological Survey of Denmark and Greenland and an affiliate of the Energy Technologies Area of Lawrence Berkeley National Laboratory (USA).

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