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Perspective

Mining resources from water

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While water itself is an essential resource for humans, water is also an important carrier of many other valuable resources with growing importance in today's world. In the face of accelerating climate change and the continued growth of the already near eight-billion global population, we are in an urgent need for a transition to a sustainable and circular economy (Kümerer et al., 2020). Achieving such a transition requires a systematic re-evaluation and optimization of the material flows of resources through different industrial sectors. It also demands novel technologies to tap into unconventional sources, such as waste streams or economically nonviable sources in the traditional sense, for scarce resources. Many of these unconventional sources are in the form of aqueous solutions, including municipal wastewaters, seawater, different types of brine deposits, and various industrial waste streams. In this mini perspective, we will briefly discuss the several major opportunities for resource extraction or recovery from aqueous sources and give an overview of the technologies for harnessing these opportunities. We will cover three major types of waters, including municipal wastewater, brines, and industrial wastewater, and discuss the type of resources that are potentially extractable from these aqueous sources (Fig. 1)

Nutrient and Energy from Municipal Wastewater A large amount of municipal wastewater is generated every day (e.g., about 100 million cubic meters per day in the US). Conventional municipal wastewater treatment is an energy-consuming process, which accounts for 1-4% of the total energy consumption in developed countries. The energy cost at a municipal wastewater treatment facility can exceed 30% of its total operational cost. However, municipal wastewater contains about five times more embedded energy than is needed for its treatment. The embedded energy is mostly chemical energy in the form of decomposable

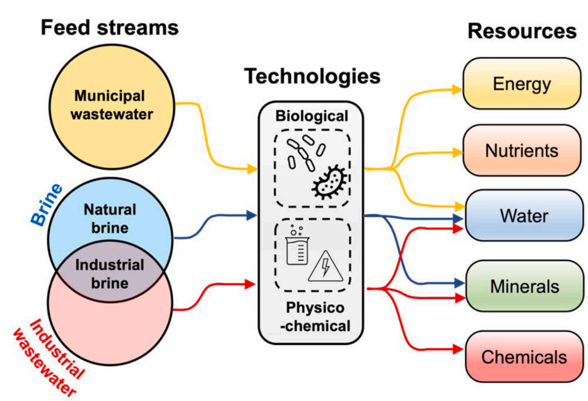

Fig. 1. A summary of various of resources (right column) that may be extracted from different types of aqueous streams (left column)

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organic matter, usually quantified using chemical oxygen demand (COD). COD is the concentration of oxygen required to achieve complete oxidation of the organics. Typical wastewater has a COD value of ~0.5 kg m^{-3}, equivalent to an energy density of ~7-8 MJ m^{-3} (McCarty et al., 2011). Additionally, as municipal wastewater typically maintains a temperature between 10 and 20 °C year-round in the treatment facility, it is also an excellent heat reservoir for operating a heat pump to provide heating in the winter and cooling in the summer. Recovering thermal energy from wastewater has received increasing attention in recent years.

Importantly, municipal wastewater is also rich in nutrient elements such as organic nitrogen and phosphorus (typically 30 and 10 g of N and P elements per m^3). Discharging these nutrients into aquatic systems may cause eutrophication and algal blooms, thus there is a rapid rate of implementing stringent regulations worldwide to curb these environmental impacts. While early approaches to address this challenge focused on nutrient removal through treatment, recent research efforts have increasingly emphasized the nutrient capture and recovery for meeting fertilizer needs of agriculture. Nutrient capture and recovery is an attractive approach because the production of ammonia via the conventional Haber-Bosch process is energy intensive and has a high climate footprint, and phosphorous is an exhaustible resource currently extracted mainly via rock mining. Cost-effective nutrient recovery from municipal wastewater or its treatment byproducts (e.g., sludge or biosolid) will both compensate the cost of the treatment facility and at the same time enhance the global agricultural sustainability.

Minerals from Brines. Brine (i.e., salt water) represents a large aqueous source of valuable minerals. In contrast to in-situ leaching that extract minerals from solid deposit using chemical leaching to alter either the redox state or pH of the ores, extracting minerals that are already present in natural or industrial brines can be substantially less chemical-intensive and more environmentally compatible. Major types of brines include seawater, salt-lake brines, shallow brine beneath dry lakes, deep groundwater and brines in geologic formations, and industrial brines. One of the most common practices of mineral extraction from brine (i.e., brine mining) is the production of sea salt from seawater, although many other types of more valuable resources can also be extracted from seawater or desalination brine. Other common chemicals that have been produced commercially using brine extraction include sodium sulfate (Na_2SO_4), soda ash (Na_2CO_3), potash (a mixture of potassium salts), boron, iodine, and lithium.

The mining of strategically important elements from brine has received substantial interest in recent years (Pramanik et al., 2020). For example, extraction of lithium from brine has become increasingly important due to the rapidly growing demand for lithium-based batteries for electric vehicles and grid storage of renewable energy. Existing lithium reserves in the form of lithium-rich brine are mostly located in several countries including Chile, Argentina, Australia, and China. The consideration of national resource security has incentivized developed countries to explore extraction of lithium from low-concentration sources such as geothermal brine, oil and gas produced water, or even seawater. The same situation also applies to rare earth elements, driving active research to develop new technologies to economically extract rare earth elements from unconventional sources such as produced water and geothermal brine. In general, the economic viability of extracting minerals from a certain brine source depends on the commercial value of the minerals and the technical difficulty of extraction.

Chemicals from Industrial Wastewater. Industrial wastewaters, including industrial brines, are generated from a wide variety of manufacturing processes, mining, oil and gas production, and power generation. Manufacturing processes with significant water consumption include, but are not limited to, metal production and finishing, textile manufacturing, paper and pulp, chemical manufacturing, and food processing. Many of these wastewaters are considered hazardous waste and typically require proper onsite treatment to minimize detrimental environmental impacts. While the treatment of specialized industrial wastewater can be costly, the reuse of industrial wastewater can benefit from the recovery of freshwater, and in many cases, valuable minerals, and chemicals to offset the treatment cost. For example, metal recovery from mining wastewater and metal processing wastewater has been practiced. Innovative approaches for dye recovery and acid/base regeneration from textile wastewater have also been investigated.

Resource recovery from industrial wastewater is highly industry specific. In some cases, the chemicals recovered are the product itself, and thus recovering chemicals from processes wastewater means enhancing the product yield. In other cases, chemicals (e.g., acid/base, solvents, and additives) are recovered for beneficial reuse within the same industry to reduce the overall chemical use, or in a different but co-locating industry as a form of industrial symbiosis.

Technologies Extracting resources from aqueous solutions typically involve a treatment train comprising multiple unit processes. Unit processes can be classified into biological and physicochemical processes based on their working mechanism; or into chemical conversion and separation processes based on the achieved function. Biological processes are typically more economical for processing dilute waste streams with COD and nutrients, and have been extensively used in treating municipal wastewater and certain industrial wastewater for both water reclamation and energy recovery. Novel processes hybridizing biological and physicochemical processes, such as membrane bioreactors and bio-electrochemical treatment systems, have gained substantial momentum in R&D and industry adoption.

However, biological processes alone are usually insufficient when it comes to recovering resources beyond energy and water. Various separation processes, such as adsorption (including electro-sorption), ion exchange, membrane separation, and thermal evaporation are often employed for mineral extraction from brine and chemical recovery from industrial wastewater. Chemical conversion processes based on precipitation, redox reaction (including electrochemical reaction), and chelation are useful for resource extraction and recovery from brines and industrial wastewater. For example, struvite precipitation is often paired with municipal wastewater treatment for phosphorous recovery. Notably, zero liquid discharge, which typically requires the integration of multiple technologies, has been actively explored as a strategy to minimize the environmental impacts of and maximize resource recovery from industrial wastewater (Tong and Elimelech, 2016). The selection and integration of unit processes must holistically consider both the feed composition and treatment goal. When treating municipal and industrial wastewaters, the treatment goal often has multiple objectives, including both compliance of environmental regulations and waste valorization.

Prospect and Research Needs The ability to efficiently extract various resources from aqueous solutions can enable two broad categories of applications to promote sustainability. The first is the extraction of minerals from various natural brines, including those that are currently not economically competitive sources for certain resources. For example, extracting lithium from seawater or produced water is technically feasible but currently cannot compete economically with production from lithium-rich brines. However, as the demand for lithium increases, the price (value) of lithium will continue to increase and thus decrease the cost differential that exists between lithium mining from conventional and unconventional sources. The continuous increase of lithium demand will also motivate the development of new technologies for extracting lithium from the unconventional sources.

The secondary category of applications concerns resource recovery from municipal and industrial waste streams to improve the economic circularity and sustainability. Following the principle that “wastes are misplaced resources”, what have been traditionally considered as waste streams can become sources of valuable resources such as nutrients, minerals, valuable chemicals, energy, and water. Recovering these resources in a cost-effective manner will reduce the cost of wastewater management or even converting it from a currently cost-intensive and regulation-driven practice to a profit generating business.

Technically, separation plays a central role in most of these applications. We envision that highly selective separation processes that can efficiently extract specific components from an aqueous solution of complex composition would be critical to effective resource mining from aqueous feed streams. Additionally, more energy-efficient and cost-effective approaches for brine treatment will benefit both resource extraction from brine and zero liquid discharge (when it is required for industrial wastewater management). As most of these applications cannot be achieved with a single unit process and many feed streams contain multiple types of resources, synergistic integration of unit processes via function-driven design and model-driven system optimization is as important for cost-effective resource recovery as developing innovative and high-performance unit processes. Beyond process optimization, we also need to adopt a more holistic approach to consider the life cycle impacts of resource extraction and recovery strategies, and to understand the impacts of their implementation on related industries and the resource supply chains. Lastly, achieving real improvement on sustainability also requires considering not only the people, the planet, but also the profit level, i.e., the "triple bottom line"(Elkington., 1997). Innovative sustainability technologies are not practically meaningful until they find adoption in economically viable applications, which highlights the importance of cost consideration in technology development and the importance of performing technoeconomic analysis.

Declaration of Competing Interest

The authors declare no competing financial interest.

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