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Editorial: Materials for next-generation energy conversion and storage

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Editorial on the Research Topic
Materials for next-generation energy conversion and storage

Humanity's concerns about the limits of progress can be traced back to John Stuart Mill's seminal book, *Principles of Political Economy*, published in 1848. In this influential text, Mill questions the relentless pursuit of economic growth and its potential consequences for future generations. In a recent research, Johan Rockström and colleagues identified nine planetary systems (Rockström et al., 2009), which includes land use change, biodiversity loss, atmospheric aerosol loading, chemical pollution, climate change, ocean acidification, stratospheric ozone depletion, nitrogen and phosphorus cycles, and global freshwater usage, along with their safe boundaries essential for maintaining the Holocene's stability. Several of these boundaries, specifically those related to biodiversity, climate change, and the nitrogen and phosphorus cycles, have already been breached (Steffen et al., 2015). Materials and energy are fundamental indicators of human progress, yet they bear a significant share of the responsibility for environmental degradation, including the pollution of land, water, and ecosystems. The quest for next-generation materials for energy production and storage has thus become crucial for achieving sustainability. This Research Topic in *Frontiers in Materials* is our contribution to addressing these critical challenges, and we hope it advances the dialogue and research in this vital area for the future of humanity.

Material sourcing, processing, transportation, and end-use management constitute the largest emission-producing sector, with fossil fuel-derived energy being particularly notorious for its environmental impact. As such, radical changes are imperative in how we source, process, and utilize these materials. The concept of a circular economy for materials has emerged as a guiding principle for the development of next-generation materials (Ramakrishna and Jose, 2022). This approach aims to foster a healthy living environment and promote sustainability by eliminating or reducing greenhouse gas emissions, resource depletion, and waste.

Next-generation materials must embody circularity, allowing them to be reused or repurposed efficiently. They should be designed with simple configurations to facilitate effective recycling. Materials with high durability can remain in use for extended periods, thus minimizing the need for further resource extraction. Sourcing these materials from renewable resources, such as non-edible biomass offers numerous advantages, including carbon negativity, environmental benignity, support for natural habitats, and benefits for human health, while also preventing these materials from ending up in landfills. Furthermore, multifunctional materials can broaden their application domains, reducing the need for different material combinations to serve various purposes.

While there are many potential pathways to develop materials with these characteristics, only a limited number of protocols are currently known. Most efforts in sustainable industrial materials focus on carbon, cellulose, lignin, and medicinal molecules. When sourced from biomass, all these materials are carbon-negative, as they sequester carbon dioxide from the atmosphere during their growth. Additionally, these biomass-derived materials are inherently multifunctional; for example, carbon can be utilized across diverse fields, including energy, electronics, environmental applications, bio-imaging, and medicine.

Energy, as a fundamental part of our lives, has played a pivotal role in shaping modern society. For nearly three billion years, up until the first industrial revolution in the 18th century, life on Earth maintained the stability of the Holocene by relying on bio and natural energy sources. However, the advent of artificially generated energy, whether in the form of pressurized steam or electricity, has drastically accelerated concerns about sustainability in a mere fraction of Earth's history—just over two hundred years.

These environmental challenges were swiftly recognized, prompting a return to natural energy sources such as solar, wind, and tidal power, which can be effectively converted into electricity or heat. Since the second industrial revolution, electricity has become integral to modern life due to its ability to be engineered for superior efficiency compared to other energy forms like heat, which suffers from significant losses during use.

Currently, numerous protocols are employed to generate electricity from natural sources like sunlight or wind on a large scale. Globally, there is an intense focus on developing technologies to enhance the conversion efficiency of these sources while also exploring new, cleaner alternatives. Ongoing research is particularly concentrated on maximizing the efficiency of converting sunlight into electricity, with efforts directed towards developing materials that can absorb a significant portion of incident light, as demonstrated by Ali et al. as well as improving the photon-to-electricity conversion process.

The intermittency of renewable energy sources, coupled with the growing demand for miniaturization, has driven significant advancements in energy storage technologies. Electrical energy storage is achieved by accumulating electrical charges on an electrode to create an electric potential. The specific method of charge storage and the origin of this potential differentiate various storage technologies. Currently, lithium-ion batteries, which use lithium ions as the charge carrier, dominate the market due to their high and reliable energy density.

However, electrochemical capacitors represent another promising avenue, particularly for their high-power capabilities, as demonstrated by (Kordek-Khalil et al.) The success of lithium-ion battery technology has spurred the development of new, cleaner industries and applications, such as electric vehicles, in an effort to reduce emissions from major polluting sectors. Yet, despite being heralded as clean technology, lithium-ion batteries come with significant material and energy costs: processing one ton of lithium emits approximately 20 tons of carbon dioxide, consumes around 1.9 million liters of water, and requires over 150 GJ of energy, with additional impacts from electrode and electrolyte processing (Ramasubramanian et al., 2024). Moreover, the energy density of lithium-ion batteries is still far lower than that of conventional fossil fuels.

Consequently, there is intense global research into new battery concepts featuring novel materials, such as earth-abundant metals, nanomaterials, and bionanomaterials. Promising investigations include metal-air batteries, which could potentially match the energy density of fossil fuels, and self-rechargeable energizers, which could conserve natural energy by storing it as electrical charges (Ling et al., 2022). Significant progress has also been made in harnessing vibrational energy through piezoelectric materials, with Cao et al. making notable contributions in this area.

We are hopeful that researchers around the world will succeed in developing materials with reduced material and energy footprints for energy conversion and storage, contributing to a more sustainable planet.

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