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Teaching electrochemistry in schools: the need for a paradigm shift to address the energy transition

La enseñanza de la electroquímica en las escuelas: la necesidad de un cambio de paradigma para abordar la transición energética

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ABSTRACT
The resilience required of students aged 12 to 15 to navigate the transition towards an increasingly electronic and electrified world represents both a significant challenge and a valuable opportunity to strengthen the teaching of electrochemistry as a fundamental component of contemporary education. Today, it is increasingly important to present complex information in an accessible and engaging manner, particularly content related to electrochemical devices and emerging technologies that are transforming society as it moves away from fossil fuels towards fully electrified systems. This study adopts a quantitative, descriptive, and interdisciplinary approach that integrates authentic educational practices, practical applications of electrochemistry, and their links to global challenges. In doing so, it seeks to ensure that future generations are adequately prepared to address the energy, social, and environmental demands of the twenty-first century. The aim of this research was to characterise secondary school students' perceptions of their knowledge of electrochemistry and its relevance to everyday life, thereby supporting the integration of this discipline into school curricula within the context of the ongoing energy transition.

Keywords: electrochemistry, energy transition, science education, sustainability

RESUMEN
La resiliencia requerida por los jóvenes estudiantes de entre 12 y 15 años para enfrentar la transición hacia un mundo electrónico y electrificado representa un desafío significativo y, al mismo tiempo, una oportunidad para potenciar la enseñanza de la electroquímica como área fundamental dentro de la educación de hoy. En la actualidad, es cada vez más relevante entregar información compleja de manera accesible y atractiva, especialmente aquella relacionada con dispositivos electroquímicos o tecnologías emergentes, ya que constituyen áreas que están transformando el mundo frente a la necesidad de abandonar los combustibles fósiles y avanzar hacia sistemas totalmente electrificados. El estudio se basa en un enfoque cuantitativo descriptivo e interdisciplinario, que combina experiencias educativas reales, aplicaciones de la electroquímica y su conexión con los desafíos globales, asegurando que las futuras generaciones estén preparadas para enfrentar los retos energéticos, sociales y ambientales del siglo XXI. El objetivo de este estudio fue caracterizar las percepciones de estudiantes de secundaria sobre el conocimiento y la relevancia de la electroquímica en su vida cotidiana, con el fin de fundamentar la incorporación de esta disciplina en la educación escolar en el contexto de la transición energética.

Palabras clave: electroquímica, transición energética, educación científica, sostenibilidad

INTRODUCTION

Electrochemistry is a branch of chemistry that studies the relationship between electrical energy and chemical energy. It is also capable of linking chemical and biological processes (Ciriminna *et al*., 2023) from the perspective of energy generation, storage, and transformation (Kempler *et al*., 2021). Its relevance has become evident in technologies aimed at the energy transition, such as (i) lithium-ion batteries, (ii) green hydrogen, and (iii) fuel cells (Kempler *et al*., 2021), which already have multiple applications today. Another common application lies in the development of biosensors and electrochemical sensors designed to detect chemical substances in the human body without the need for blood extraction. However, the teaching of electrochemistry at all educational levels is limited or almost non-existent and is largely based on the concept of "renewable energy", which is now outdated (Elgrishi *et al*., 2018). This work addresses this educational gap, highlighting that current school curricula (Turner *et al*., 2024a) are not well structured to respond to the needs of an electrified world. For example, notable advances have been made in the United Kingdom, South Africa, and Israel in the teaching of electrochemistry at the university level (Turner *et al*., 2024b; Rollnick & Mavhunga, 2014; Karamustafaoğlu & Mamlok-Naaman, 2015). Nevertheless, electrochemistry is not currently integrated into primary or secondary education in Latin America and remains focused on undergraduate and postgraduate students, with an emphasis on solving complex algorithmic problems rather than on practical or playful activities (Tsaparlis, 2019).

Thanks to chemistry, cellular-level processes are now understood in much greater detail. According to the membrane theory of nerve excitation, originally proposed by Julius Bernstein in 1902, neuronal membranes (nerve cells) can become electrically polarised by blocking or transmitting specific ions. As demonstrated by David Nachmansohn in 1938, this polarisation travels along the nerve until it reaches its end, where it triggers the release of a chemical substance known as acetylcholine. This substance causes the polarisation of adjacent neurons, transmitting the impulse to its destination, whether a muscle, another nerve, or another organ. When the nerve signal reaches a muscle, it initiates a chain of chemical reactions that result in the breakdown of a molecule called adenosine triphosphate (ATP). When the ATP molecule is broken down, electrochemical energy is released.

Other relevant applications include medical devices such as pacemakers, generators, and hearing aids, which rely on miniaturised batteries. In addition, the development of electrochemical techniques in medicine makes it possible to study how cardiac muscle cells (cardiomyocytes) generate an action potential associated with a contractile response to a stimulus. This potential involves changes in the membrane potential due to the activation of various ionic currents, allowing ions to diffuse across the membrane according to their electrochemical gradient. The detection of electrical potentials is also applied in electrocardiography (ECG). Measuring the electrical activity of the heart is essential for assessing cardiac function and detecting abnormalities, as it allows the recording of heart rate and rhythm, the size and position of the heart chambers, and possible lesions. Understanding these technologies enables students to appreciate the presence and tangible impact of electrochemistry on human quality of life (Scholz, 2024).

METHODOLOGY

This study corresponds to a descriptive research design with a quantitative and cross-sectional approach, the purpose of which was to characterise secondary school students' perceptions of electrochemistry and its relationship with technologies associated with the energy transition within a specific territorial context. The survey items were aligned with the conceptual framework of the study and the Sustainable Development Goals (SDGs 4, 7, and 13), considering the link between scientific literacy and the energy transition.

The research was conducted in the Atacama Desert, Chile, at the *Liceo Bicentenario Agropecuario Likan Antai*, located in San Pedro de Atacama, an area of high solar irradiance where energy-related topics acquire both educational and socio-environmental relevance. The sample consisted of 143 secondary school students aged between 12 and 15 years. A perception questionnaire was used as a preliminary diagnostic instrument for scientific literacy. It comprised closed-ended, single-response questions using Likert-type rating scales, as well as categorised questions. The questionnaire was administered in person during a science class under the supervision of schoolteachers, with data collected through digital questionnaires.

RESULTS

The results show that 98% of students consider the search for new energy sources to be relevant (Fig. 1), and more than 75% recognise that chemistry plays a fundamental or important role in the development of clean energy technologies (Fig. 2), indicating an appropriate perception of the link between science and sustainability.

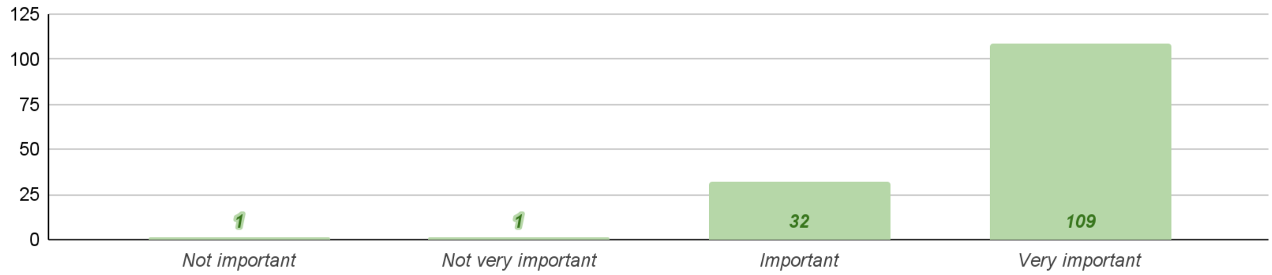

Fig. 1: The graph shows the distribution of responses to the question: "How important do you think it is to search for new energy sources for the future?

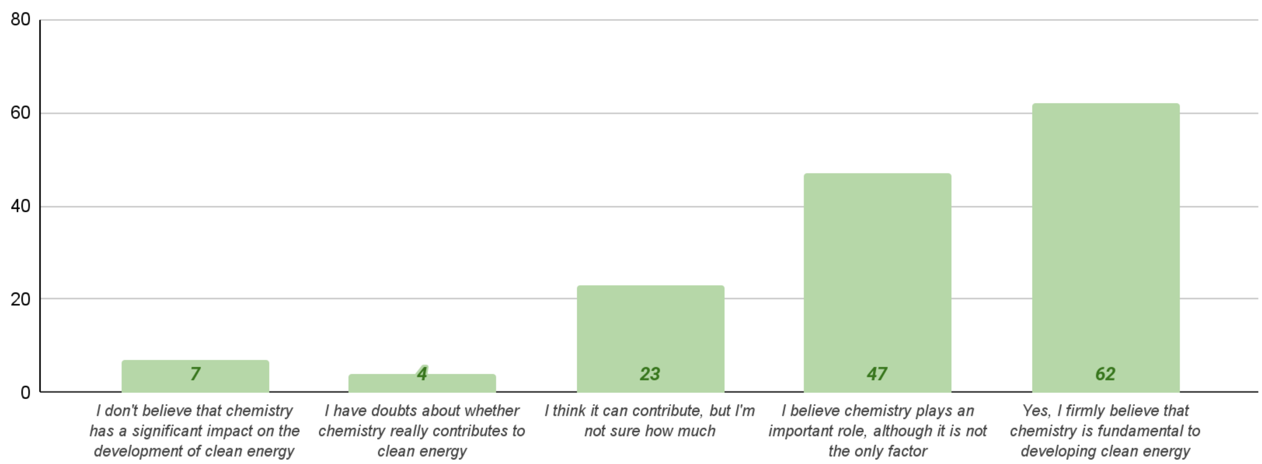

Fig. 2: Student's perceptions of the potential of chemistry to contribute to the development of clean energy.

In contrast, only 14.1% of respondents report being familiar with several concrete applications of electrochemistry in their everyday lives, suggesting a limited internalisation of electrochemical principles despite their relevance in widely used and disseminated technologies. The majority indicate that they are unclear about how this field is integrated into the technologies they encounter daily, or state that they do not know of any current applications of electrochemistry (see Fig.3).

Another relevant finding of the study is that 71.1% of students express interest in learning about renewable energy through experimental activities, which highlights the need to integrate experience-based pedagogical approaches to promote meaningful understanding of the electrochemical processes associated with the energy transition. It is noteworthy that the strongest preference is for carrying out these learning activities under teacher guidance, revealing the importance of teacher training in both subject content and teaching methodologies (see Fig. 4).

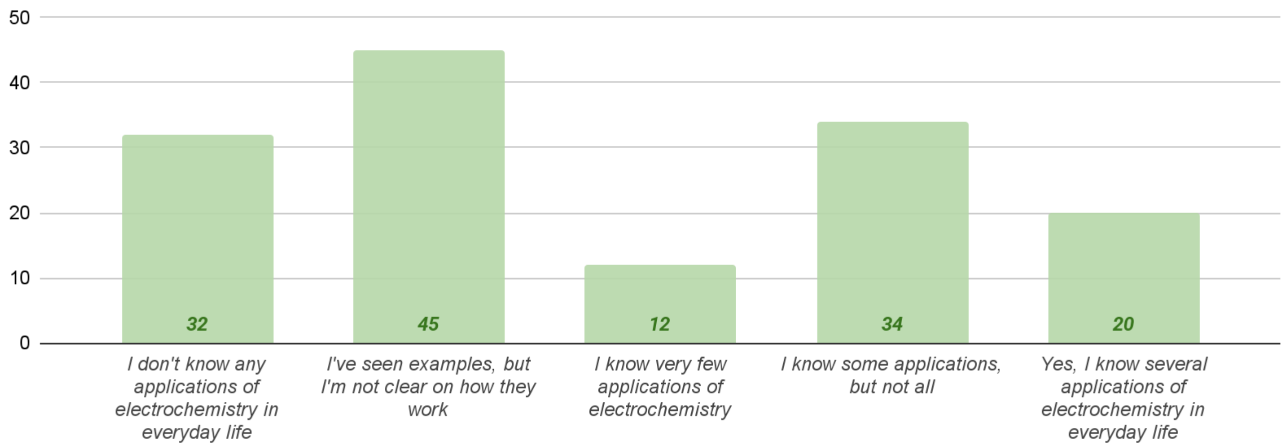

Fig. 3: Students' perceptions of everyday applications of electrochemistry.

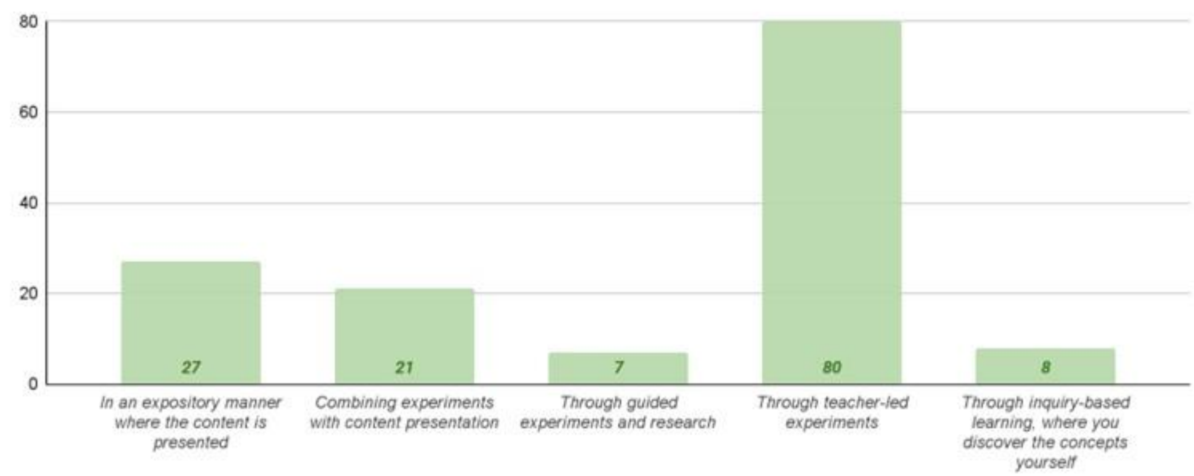

Fig. 4: Preferences regarding learning approaches to renewable energy in science classes.

DISCUSSION

As early as 1992, Garnett et al. conducted a study with final-year secondary school students in Australia following a 7–9-week course on electrochemistry. Through semi-structured interviews with 32 students, they identified multiple persistent misconceptions, such as confusion regarding the direction of electric current, electrode polarity, and the operating mechanisms of both galvanic and electrolytic cells. The findings revealed that even after receiving formal instruction, students retained alternative conceptions that were incompatible with accepted scientific knowledge (Garnett & Treagust, 1992), highlighting the need to develop new teaching methodologies to address these contents

Likewise, Özkaya (2002) examined the teaching and learning processes of redox reactions and electrochemistry at the secondary school level. The study showed that both students and teachers experienced substantial difficulties in understanding and explaining concepts such as electrochemical equilibrium, cell potential, and the functioning of oxidation–reduction reactions. This work, published in the Journal of Chemical Education, demonstrated that traditional teaching approaches based on memorisation and the isolated treatment of concepts do not promote the construction of meaningful learning in this area (Özkaya, 2002).

In a complementary manner, several subsequent empirical studies have documented the significant difficulties that secondary school students continue to face in understanding fundamental concepts of electrochemistry. For example, Akram *et al.* (2014) conducted a study with ninth-grade students in secondary schools in Pakistan, in which they applied a diagnostic test known as the TCDE. The results indicated that approximately 67% of the assessed items were considered difficult by the students. The main causes identified were weaknesses in prior knowledge, a lack of appropriate teaching resources, and the use of technical language that was not easily accessible (Akram *et al.*, 2014). These studies clearly demonstrate that the teaching of electrochemistry at school level requires a thorough curricular and methodological revision, aimed at overcoming the conceptual barriers that have historically hindered student learning. The implementation of innovative and contextualised teaching strategies is essential to improve understanding of a discipline that is central to the energy and technological transition of the twenty-first century. This is because knowledge of chemistry and electricity is fundamental for educating pioneers of new technologies applicable across diverse fields of knowledge. In this line of reasoning, the analysis makes it possible to identify the existence of a structural critical bottleneck in the teaching of electrochemistry at school levels, particularly in secondary education. This bottleneck is reflected in the persistent conceptual difficulties faced by both students and teachers in understanding, teaching, and applying the fundamental principles of this scientific discipline. Research shows that school curricula tend to address electrochemistry in a fragmented and decontextualised manner, with limited connection to contemporary technological advances, thereby restricting its educational potential. In addition, the prevalence of traditional methodologies centred on the passive transmission of content, the lack of specialised teacher training, and the near absence of articulation between curricular content and real or emerging twenty-first-century challenges—such as the energy transition, environmental sustainability, and medical technology—further compound this issue.

The effects of this bottleneck are profound and multifaceted. First, it generates a cognitive gap that prevents students from understanding the electrochemical processes underlying technologies that are widely used today, such as lithium-ion batteries, energy storage systems, green hydrogen production, and biosensors. This disconnection not only compromises the development of fundamental scientific competencies but also reduces the ability of future citizens to interpret, participate in, or innovate within contexts shaped by the advancement of clean technologies.

Second, misconceptions about key concepts such as polarity, electron flow, and cell potential persist even after formal instruction, reflecting insufficient and poorly meaningful teaching. Furthermore, the opportunity to use electrochemistry as an integrative axis for interdisciplinary knowledge is missed, thereby limiting its formative value in the development of complex scientific thinking.

It is therefore imperative to justify the need to address this issue, given the central role of electrochemistry in the processes that are currently transforming productive, energy, and social structures on a global scale. Electrochemistry is a discipline with a high degree of practical applicability, capable of linking chemical and biological processes to innovative solutions in fields as diverse as energy, health, and the environment. The absence of structured and up-to-date teaching in this area represents a curricular deficiency that affects not only scientific learning, but also civic education and equity in access to technological knowledge. As noted by Brett and Oliveira-Brett (2024), the teaching of electrochemistry must move beyond the school laboratory and respond to contemporary social and technological challenges, providing students with the tools to interpret and actively participate in an electrified world.

From the field of educational research, addressing this critical bottleneck requires a rigorous and systematic approach that makes it possible to understand its causes and to propose sustainable solutions. It is pertinent to explore students' conceptual representations in depth, analysing the most frequent difficulties and their possible origins. It is equally necessary to examine how electrochemistry is addressed in curricula, textbooks, and available pedagogical resources, to identify gaps, outdated content, and opportunities for improvement. In parallel, it is essential to investigate teaching practices and the conditions of initial and ongoing teacher training, given that both disciplinary and didactic mastery of electrochemistry are key factors in its effective teaching.

From the perspective of the energy transition, fuel cells and electrolysis to produce green hydrogen are key technologies for decarbonising the energy sector, offering clean solutions for energy storage and transport. In addition, emerging technologies such as supercapacitors and flow batteries present opportunities to optimise large-scale energy storage, facilitating a more efficient transition towards a sustainable energy system. Battery recycling and the recovery of critical metals depend on advanced electrochemical processes. Early education in these areas promotes environmental awareness and practical scientific knowledge. This approach is also known as the circular economy. Developing efficient recycling processes not only reduces environmental impact but also creates economic opportunities. Including these topics in school education prepares students to contribute to these innovative solutions (Orozco *et al.*, 2023).

The teaching of electrochemistry in schools presents several challenges, including: (i) Conceptual complexity: Topics such as redox reactions, electron flow, and electric potential are abstract and require careful simplification. Introducing these ideas can benefit from the use of digital tools, such as interactive simulations that visualise the movement of electrons in a galvanic cell; (ii) Resource limitations: The lack of well-equipped laboratories and accessible materials hinders practical experimentation (Tsaparlis, 2019). Strategies such as "at-home laboratory kits" designed for students can help mitigate these limitations by allowing them to explore key concepts using everyday materials; (iii) Teacher training: Many educators lack specific training in applied electrochemistry and sustainable energy topics. Continuous professional development programmes, combined with clear instructional resources, can help bridge this gap and enable teachers to teach these topics effectively.

Addressing these challenges requires a collaborative effort among educators, policymakers, and researchers. The proposed strategies aim to make electrochemistry accessible and relevant, encouraging students to engage with scientific and technological advances. Including electrochemistry modules in school curricula not only provides technical skills but also inspires students—particularly girls—to consider careers in STEM (Krushinski *et al.*, 2024). Practical activities and projects linked to real-world problems stimulate creativity and innovation, preparing future generations to contribute actively to a more sustainable world. The proposed educational approach also has potential impacts on job creation and the reduction of inequalities. Early training in energy and sustainability equips students with critical competencies that are highly demanded in emerging sectors, contributing to a more inclusive and resilient economy.

The use of analogies and metaphors to make abstract concepts more tangible could be an effective strategy. For example, comparing the flow of electrons in a circuit to the flow of water in a pipe facilitates initial understanding. Designing simple experiments, such as homemade batteries and demonstrations of water electrolysis, can further reinforce these concepts. These experiments can be extended to include the construction of a hydrogen-based fuel cell prototype. Integrating interdisciplinary projects makes it possible to link electrochemistry with topics in technology, mathematics, and environmental science. Moreover, incorporating electrochemistry as a cross-cutting theme in the curriculum can be achieved by connecting topics such as the environmental impact of batteries with practical solutions for recycling and reuse. Likewise, the use of online learning communities enables teachers to share experiences and effective pedagogical resources.

In this context, strengthening the teaching of electrochemistry at school levels represents a direct contribution to the commitments established in the 2030 Agenda for Sustainable Development. In particular, it aligns with Sustainable Development Goal (SDG) 4, which promotes inclusive and equitable quality education and fosters lifelong learning opportunities. Integrating updated and meaningful electrochemistry content into curricula, linked to real and emerging issues, not only improves educational quality but also democratises access to key knowledge for the energy and technological transition. This approach helps to educate students with critical thinking skills, scientific competencies, and environmental awareness, enabling them to contribute to the transformations required for sustainable development.

Likewise, this educational proposal should be closely linked to SDGs 7 and 13, which seek to ensure access to affordable, reliable, sustainable, and modern energy for all. Electrochemistry is a fundamental discipline in the development of clean technologies such as rechargeable batteries, energy storage systems, fuel cells, and green hydrogen (ONU, 2015). By teaching these topics from an early stage, the education of future generations is strengthened, preparing them to research, innovate, and apply sustainable energy solutions. In this way, a scientific culture committed to sustainability is reinforced, and the foundations are laid for progress towards low-carbon, technologically literate, and socially responsible societies, in line with the principles of the 2030 Agenda.

The results of this study should be interpreted considering certain methodological limitations. First, the research was conducted in a single educational institution in the municipality of San Pedro de Atacama, which limits the extent to which the findings can be generalised to other educational or territorial contexts. In addition, the data correspond to a descriptive diagnosis of students' perceptions based on a closed-ended questionnaire and therefore do not allow for an in-depth exploration of the underlying reasons behind the opinions expressed by the students.

In relation to the above, the survey did not directly assess students' conceptual knowledge of electrochemistry, but rather only their everyday perceptions. Therefore, future research could be complemented with diagnostic tests focusing on science content related to this area. Despite these limitations, the findings constitute an initial empirical approach to electrochemical literacy among students in regions of high solar irradiance and provide a basis for subsequent studies aimed at the design and implementation of innovative pedagogical proposals within the context of the energy transition.

CONCLUSIONS

A significant gap in electrochemical literacy in schools is evident, alongside a high level of student interest in learning about these technologies in the context of the energy transition. This confirms that the absence of up-to-date content and teaching methodologies does not stem from a lack of motivation or a lack of contextual relevance, but rather from a curricular and didactic shortcoming that limits access to and understanding of essential processes in an electrified world. Integrating electrochemistry and its applications into curricula through active methodologies and accessible, engaging resources would enable the development of scientific competencies, critical thinking, and informed energy citizenship, thereby contributing to the achievement of SDGs 4, 7, and 13. To advance this paradigm shift, coordinated efforts are required among educational communities, teacher training institutions, universities, and public policy bodies to strengthen school infrastructure, professional development, and the production of contextualised teaching materials. Integrating electrochemistry into school curricula is essential to prepare future generations for an electrified world. Active methodologies and appropriate resources will make this discipline accessible and impactful, fostering innovation and sustainability. Moreover, this approach cultivates a problem-solving mindset that is crucial for addressing the energy and environmental challenges faced by society. Therefore, it becomes strategic to design, implement, and evaluate innovative pedagogical proposals based on active and contextualised methodologies that position electrochemistry as a tool for solving real and meaningful problems. Such studies will not only document and help to understand current difficulties, but also propose didactic alternatives that promote deep learning, student motivation, and the construction of a science education aligned with the challenges of the present and the future. As schools adopt these changes, students will be better prepared to lead the transition towards a sustainable future.

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