Perspective

Electrochemical separation processes for future societal challenges

Greg A. Mutch1,2,*

SUMMARY

Electrochemical separation processes can be highly efficient when they act on specific target species. This is only possible in practice when high-selectivity, redox-active materials are paired with an electrical driving force in a cost-effective, practical device. Thus, this perspective seeks to highlight developments in, and associated challenges for, electrochemical separation processes aimed at tackling prominent societal challenges, including greenhouse gas removal from air, recovery of valuable metals from seawater, recycling electronic wastes, and ensuring equitable access to energy, food, water, and healthcare. While specific examples show real promise for deployment, more realistic studies using complex, multi-component mixtures and long-term testing of promising devices to enable rigorous techno-economic analyses are highlighted as pervasive challenges.

INTRODUCTION

In practice, all substances are mixtures. Therefore, processes to separate and purify substances account for 10%–15% of global energy consumption1 and 40%–90% of capital and operating costs in industry.2 Despite their scale and importance, separation processes are “often overlooked and underappreciated” and the teaching of separation science and engineering is outdated.3

Pivotal problems in the expanding climate, energy, materials, food, water, and health sectors will make separation processes even more prevalent than they are today. Transformative science and engineering will be required to source and recover materials from ever more dilute and complex mixtures and to reduce the energy intensity of separation processes.1,3 A transition in the way we design and power separation processes is now a decisive step in the pursuit of sustainability.

The necessity of such a “separations transition” cannot be understated (Figure 1). Removing fossil-fuel-derived greenhouse gases from air is already needed to limit global warming to 2°C,4,5 yet the removal of carbon dioxide using existing engineered separation processes in 2100 would require more than half of today’s final global energy consumption.6 These processes are very energy intensive, as carbon dioxide is very dilute in air, currently ~400 ppm. Recently, there have even been calls for atmospheric methane and nitrous oxide removal (~2 and 0.3 ppm in air, respectively).7–9

Transitionsing away from fossil fuels will require vast quantities of lithium (and nickel, cobalt, etc.) for batteries and uranium for nuclear reactors. Seawater is now considered an untapped source ("mining the sea"), as there are approximately three orders of magnitude more lithium and uranium in the sea than on land.11,12 They are present, however, at ~200 and ~3 ppb, respectively.

1Materials, Concepts and Reaction Engineering (MatCoRE) Research Group, School of Engineering, Newcastle University, NE1 7RU Newcastle-upon-Tyne, UK
2Centre for Energy, Newcastle University, NE1 7RU Newcastle-upon-Tyne, UK
*Correspondence: greg.mutch@newcastle.ac.uk

https://doi.org/10.1016/j.xcrp.2022.100844
Widespread electrification to support the energy transition will require considerable amounts of rare-earth metals for batteries and magnets. These are not scarce, but they have an average concentration in the Earth’s crust on the order of 100 ppm, and their similar chemical properties lead to inefficient, wasteful, and ultimately unsustainable separation processes. Rare earths are also increasingly found in e-wastes, which will compel recovery.

Figure 1. Future challenges for separation processes
(A) Scarcity of the 90 natural elements and their use in smartphones, as defined by the European Chemical Society Periodic Table (https://www.euchems.eu/euchems-periodic-table/). Scarcity of useful elements will increasingly compel resource recovery.

(B) The periodic table with examples of elements increasingly targeted for removal or recovery from sea, land, and air and/or required for energy storage and conversion processes. Seawater is a potentially large and untapped resource of the valuable metals in blue (Li, V, Co, Ni, Cu, Nb, Mo, Ag, Au, and U), taken from Table 1 in Diallo et al. Elements used to produce smartphones, colored gold, are now widely found in e-waste on land (Li, C, O, Mg, Al, Si, P, K, Co, Ni, Cu, Ga, As, Y, Ag, In, Sn, Sb, Br, Ta, Au, Pb, La, Pr, Nd, Eu, Gd, Tb, and Dy; https://www.compoundchem.com/2014/02/19/the-chemical-elements-of-a-smartphone/). The elements that make up greenhouse gases, targets for separation from point sources and direct removal from air, are colored brown (H, C, N, O, F, S, and Cl). Bold-bordered elements are required in increasing quantities to produce various batteries (H, Li, C, O, Na, Mg, Al, Si, P, S, K, Ca, Ti, V, Cr, Mn, Fe, Co, Ni, Zn, Zr, Ag, Cd, Hg, Pb, La, Ce, Pr, Nd), triangles indicate elements used as catalysts in traditional and fuel cell electric vehicles (Ru, Rh, Pd, Ag, Os, Ir, Pt, and Au), and circles highlight elements used in magnets (B, Al, Co, Ni, Cu, Zr, Nb, Nd, Sm, and Dy). All selected elements are found naturally and/or in wastes as dilute components of complex mixtures.
Achieving equitable food and water supply also necessitates separations. The Haber-Bosch process, which involves separating nitrogen from air, hydrogen from carbon dioxide, and product purification, consumes ∼1%–2% of the total energy produced today. Meanwhile, most of the world’s population faces severe, recurring water shortages. As ∼97% of all water on Earth is saline, desalination is presented as a solution in certain locations. Even harvesting from the ∼0.001% of Earth’s water in the atmosphere has been posited.

For human health, the production of monoclonal antibodies, like those used to treat coronavirus disease 2019 (COVID-19), involves multiple, distinct separation processes. Timely detection of severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2) in bodily fluids is also, primarily, a selective separation challenge.

TRADITIONAL AND ELECTROCHEMICAL SEPARATION PROCESSES

Separation processes require a selective device or material, exploitable differences in the properties of coexisting species, and a driving force to affect separation. Sometimes they also require additional reagents, such as solvents. Arguably the most familiar processes, i.e., sieving, filtration, and centrifugation, exploit differences in size or density and require an applied or gravitational force. In the chemical industry, the most ubiquitous processes (∼80% by energy consumption), i.e., distillation, drying, and evaporation, exploit differences in the enthalpy of vaporization and require heat. Membrane separation and sorption processes exploit differences in chemical structure or reactivity and require the application of heat, pressure, or vacuum. Selectivity, capacity, throughput, and stability are derived in different ways, but crucially, all the above separation processes non-selectively apply mechanical or thermal driving forces to the entire system (the mixture containing the target species, any additional reagents, and often the device or plant as well; Figure 2). Higher efficiencies could be achieved using electrochemical separation devices if the electrical driving force they use to affect separation is delivered directly (and only) to the target species (Figure 2). This is only possible when highly selective materials are employed, which represents a key challenge for such devices, discussed in detail below. Nonetheless electrochemical separation devices may offer unique advantages. Being modular by design (at the component and device scale), they derive benefits from high-volume and digital manufacturing practices (economies of scale, product change and variety, ease of repair and replacement, etc.). Modularity also means they can be distributed to where they are needed more easily than large, centralized facilities, which could, in principle, enhance equitable access to both the device and the product of separation. Finally, they integrate well with, benefit from, and enable electrification.

RECENT DEVELOPMENTS IN ELECTROCHEMICAL SEPARATION PROCESSES

Consequently, researchers have begun developing electrochemical separation devices to tackle the future separation challenges identified above. Advances in these areas are reviewed below while highlighting the challenges that researchers must tackle to overcome the significant barriers to entry for such technologies. A summary of challenges is provided in Table 1.

Greenhouse gas emissions
In one of the most developed processes for the removal of carbon dioxide from air, thermally driven regeneration of an aqueous hydroxide solvent is the most
energy-intensive step. In principle, electrochemical strategies to regenerate such solvents require approximately half the energy and simplify certain processes by removing the need for solids handling and a supply of heat. Often, however, the operating conditions for optimal energy demand necessitates larger membranes or electrodes, which are currently made from high-cost materials. This renders such electrochemical processes uneconomical today. For these processes to become economical, a reduction in both electricity and membrane material costs is required, alongside an order of magnitude increase in membrane lifetime. This is clearly a significant challenge.

An alternative approach for electrochemical carbon dioxide removal is to attempt to decouple membrane or electrode size from gas contacting area, e.g., liquid quinones in a flow system. However, related challenges emerge, such as a poor understanding of materials lifetime (which may drive replacement costs), as well as a
need for electrode, electrolyte, and membrane materials with high reaction rates and/or high conductivity to enable high current density. Moreover, if point source carbon dioxide capture is to be pursued using electrochemical methods (instead of carbon dioxide removal from air), the impact of common flue gas pollutants (e.g., oxides of nitrogen and sulfur) must be explored. This is a common criticism for the development of many new carbon dioxide capture materials; often they are tested in idealistic (or simplified) gas mixture compositions and under conditions far from real application.

Solid-state electrochemical carbon dioxide separation processes would remove the need for solvents entirely. In these systems, a tethered, redox-active molecule captures and releases carbon dioxide upon charge and discharge, and they have been shown to operate with ~90% coulombic efficiency over thousands of cycles. 21 A major challenge has been carbon dioxide selectivity over oxygen in the air. A recent breakthrough on that front has elicited an $80 million investment in start-up Verdox (https://www.bloomberg.com/news/articles/2022-02-02/new-tech-could-cut-carbon-capture-energy-use-by-70), which serves as a pertinent example of materials innovation enabling the further development of electrochemical separation devices.

### Metals for energy and rare and precious metals

To meaningfully pursue seawater as a source of, e.g., lithium, electrochemical sorption (intercalation) methods are (at first glance) an appealing alternative to replace time-, energy- and land-intensive, i.e., uneconomical, evaporation approaches. To make deployment a reality, however, significant materials science developments to maintain high coulombic efficiency will be required (i.e., lithium selectivity over the numerous competing ions in seawater: sodium, potassium, magnesium, calcium, iron, etc.). This represents a key example where sophisticated tuning of a materials-intrinsic selectivity for the species of interest has been necessary to demonstrate the concept. 22 Generally, research in this area must shift focus from brines (containing...
relatively high concentrations of lithium) to real seawater samples. For those that have tackled more realistic (seawater) samples, it is now necessary to demonstrate device stability over thousands of cycles instead of the few often reported in initial studies.¹¹

Electrically driven dense ceramic membrane alternatives, however, have already achieved very high coulombic efficiency, close to ~100%, and can continuously up-concentrate lithium from real seawater by four orders of magnitude. Coupling the electrochemical enrichment process with traditional precipitation methods enabled the direct production of battery-grade lithium phosphate (99.94% purity) from seawater.²³ This is a good example of traditional (bulk) separation methods working synergistically with electrochemical methods in the pursuit of increased efficiency; however, again, long-term tests are now needed.

For uranium extraction from seawater, which is much less frequently explored, although electrochemical modification of state-of-the-art amidoxime polymer sorbents results in an order of magnitude increase in sorbent capacity and significantly faster kinetics, higher coulombic efficiency is needed to reduce costs to a level that makes seawater competitive with traditional sources.¹² Again, many of the key challenges for practical application lie within the materials domain; increasing electrode surface area and limiting the formation of byproducts were identified during tests with real seawater.

Industrial wastes are also increasingly considered both for the recovery of valuable metals and as an important facet of environmental remediation. Although traditional metal-recovery technologies (pyro- and hydro-metallurgical extraction) involve large plant footprints, lengthy processes, high temperatures, expensive and corrosive chemicals, and significant concomitant wastes and emissions, they are among the best options we currently have. To mitigate some of these shortcomings, electrochemical extraction, particularly the twinning of hydrometallurgical processes with selective electrochemical metal recovery, has received increased attention.²₄,²₅ However, a research focus on simple binary mixtures, which significantly overestimates true performance, has stimulated a call to study more realistic, complex, multi-component mixtures and to more precisely define selectivity.²₅ Claims of better efficiency, cost-effectiveness, and selectivity are speculative in the absence of such rigorous studies. Moreover, without them, thorough life cycle and techno-economic studies to appraise their true potential are impossible. Unfortunately, the study of simple binary mixtures has been a pervasive practice in separation science more generally, one which the developers of electrochemical separation devices should not seek to copy.

**Food, water, and health**

A recent “electrochemical reinvention” of the thermochemical Haber-Bosch process using a ceramic electrochemical membrane reactor enables hydrogen production and purification, ammonia synthesis, and the recovery of pure carbon dioxide, all at atmospheric pressure.¹³ In principle, it could reduce the energy requirement for ammonia production, more than halve carbon dioxide emissions compared with the existing process,¹³ and provide more equitable access to ammonia.¹⁶ These are all admirable goals. However, the low surface area of ceramic electrolytes severely limits productivity, and the claims above rely on a doubling of the coulombic efficiency of the system in the future, which is hampered by materials challenges (e.g., cell component adhesion and mixing, the need for complex deposition techniques, electrode microstructure control, etc.).²₆ If steam could be used
instead of methane as a hydrogen source, this would further reduce carbon dioxide emissions. Unfortunately, challenges with the stability of today’s electrochemical membrane materials in the presence of water would impose an entire re-design of this system, and steam imposes an order of magnitude increase in electrical power costs, which is regarded as a “serious deterrent for practical applications.” More generally, ceramic membrane devices are prone to cracking due to poor mechanical strength, sealing and formation of ceramics into membrane modules is non-trivial (often requiring bespoke solutions), and functional ceramics are expensive. Again, without further studies and robust techno-economic assessments, it is difficult to assess the true potential.

Electrochemical separation approaches have also been touted as a more energy-efficient solution to desalination, where thermally and mechanically driven separation processes dominate the market. Often, electrochemical desalination devices (e.g., capacitive deionization) can be in terms of specific energy consumption, but thermodynamic efficiency is generally about one order of magnitude lower than that of mechanically driven processes. Simply put, electrochemical processes are good at efficiently removing salt, but not always for producing high-purity water. Devices using intercalation materials appear to be an important outlier. Relying on a fundamentally different ion-extraction mechanism to, e.g., capacitive deionization and with different device configurations, initial assessments suggest some have thermodynamic efficiencies similar to more traditional technologies. Moreover, as charge (and therefore energy) is partially recovered, these devices can also be used for energy storage, which with growing demand for more sustainable energy may be a technology enabler. To realize this potential, improving device stability in the presence of organic matter, demonstrating longer materials lifetime, and understanding the impact of materials costs on techno-economic feasibility (particularly in comparison with the dominant reverse-osmosis processes and on potential energy-storage integration scenarios) are all important research targets.

For water harvesting from air, electrochemical membrane devices can, in theory, halve the energy requirement for humid-air dehumidification. In one of the few practical tests of the approach, however, only ~30% of the applied power was used for dehumidification, with activation overpotential, concentration overpotential, and other losses accounting for the rest. Proof-of-concept designs for hydrogen production from water in the air have only been made possible by using very advanced (i.e., far from commercial reality) membrane materials and expensive precious metal catalysts. As with greenhouse gas removal, the effect of potential poisons (oxides of carbon and nitrogen) and long-term stability are still not understood.

As above, electrochemical separation processes for inorganic species have drawn some interest, but attention may now also turn to the organic species essential for food and medicine production. Here, the mild separation conditions and potential for more sustainable processes are especially attractive as approximately 50%–70% of the production cost of organic acids and proteins (including the antibodies mentioned above) comes from separation processes. With a noticeable scarcity of work in this sector, it is ripe for innovation. Distinct needs here include the development of novel operating modes to mitigate fouling and designs from the materials to the device scale that enable the use of non-aqueous solvents.

Finally, it should be remembered that sensors and diagnostic tests are also separation processes, as they must selectively detect an analyte of interest in a
complex mixture. The global COVID-19 pandemic has familiarized the public with the terms (and acronyms) “PCR” and “lateral flow test” (LFT). Due to the laborious and complex nature of PCR tests and the relatively low sensitivity of LFTs, rapid, simple detection at the single-molecule level has been a critical and unmet need until recently. These devices also best demonstrate the notion of an ideal electrochemical separation; whereas an analyte-binding event results in an electrical signal in a sensor, this concept “in reverse” in a separation device would deliver an electrical driving force directly (and only) to a target species (Figure 2). They also represent a compelling example of separation science, useful for tackling its “often overlooked and underappreciated” reputation.

**CONCLUSIONS AND OUTLOOK**

Separation processes allow humanity to survive (and thrive). Many of the selectivity, capacity, throughput, and stability challenges associated with traditional separation processes have been tackled successfully, and they are therefore widely deployed. However, such processes non-selectively apply a driving force to affect separation. Limited efficiencies due to this approach may render traditional separation processes inadequate for some of the major separation challenges facing humanity across the expanding climate, energy, materials, food, water, and health sectors, particularly when the dilution of the species we target, and the complexity of the mixture they are within, increases. Thus, interest in developing electrochemical separation processes has been sparked due to their theoretical potential for higher efficiencies.

Electrochemical separation devices could in some cases integrate with traditional separation processes, while in others, they may act alone to provide better efficiencies in some of these major separation challenges. Examples have been provided above for both approaches. However, in almost all cases, the efficiencies that they promise in theory now need to be realized in practice. Most often, this will be through an exquisite and intimate pairing of the intrinsic selectivity of appropriate materials with the electrical driving force. Subsequently, long-term testing will be necessary to understand temporal and physical changes at the material and device scale. Only by conducting such studies can rigorous techno-economic evaluation be undertaken, which is lacking for all the examples presented above. This will be crucial, particularly considering the scaling relationship for processes based on interfacial devices. Advances in, e.g., electrochemical carbon dioxide removal, where initial testing and demonstration followed by significant investment suggest real promise, support the notion that research on electrochemical separation processes more generally could provide important advances. Such research represents an exciting opportunity for tomorrow’s materials scientists and process engineers.

**ACKNOWLEDGMENTS**

G.A.M. was supported by the Royal Academy of Engineering under the Research Fellowship scheme. Support from the Engineering and Physical Sciences Research Council (EPSRC) via grant EP/V047078/1 and the UK Catalysis Hub funded by EPSRC grant reference EP/R027129/1 is gratefully acknowledged.

**AUTHOR CONTRIBUTIONS**

G.A.M. was responsible for funding acquisition, visualization, original draft, and review and editing.
REFERENCES

1. Sholl, D.S., and Lively, R.P. (2016). Seven chemical separations to change the world. Nature 532, 435–437.

2. de Haan, A.B., and Bosch, H. (2013). Industrial Separation Processes - Fundamentals (De Gruyter).

3. National Academies of Sciences, Engineering, and Medicine (2019). A Research Agenda for Transforming Separation Science (The National Academies Press).

4. Gasser, T., Guivarch, C., Tachiri, K., Jones, C.D., and Caia, P. (2015). Negative emissions physically needed to keep global warming below 2°C. Nat. Commun. 6, 1–7.

5. Erans, M., Sanz-Pérez, E.S., Hanak, D.P., Clulow, Z., Reiner, D.M., and Mutch, G.A. (2022). Direct air capture: process technology, techno-economic and socio-political challenges. Energy Environ. Sci. https://doi.org/10.1039/D1EE03523A.

6. Realmente, G., Drouet, L., Gambhir, A., Glynn, J., Hawkes, A., Koberle, A.C., and Tavoni, M. (2019). An inter-model assessment of the role of direct air capture in deep mitigation pathways. Nat. Commun. 10, 1–12.

7. Jackson, R.B., Solomon, E.I., Canadell, J.G., Cargnello, M., and Field, C.B. (2019). Methane removal and atmospheric restoration. Nat. Sustain. 2, 436–438.

8. Lackner, K.S. (2020). Practical constraints on atmospheric methane removal. Nat. Sustain. 3, 41893.

9. Jackson, R.B., Abernethy, S., Canadell, J.G., Cargnello, M., Davis, S.J., Fuss, S., Heyer, A.J., Hont, C., Jones, C.D., et al. (2021). Atmospheric methane removal: a research agenda. Philos. Trans. R. Soc. A. Math. Phys. Eng. Sci. 379, 20200454.

10. Diao, M.S., Kotte, M.R., and Cho, M. (2015). Mining critical metals and elements from seawater: opportunities and challenges. Environ. Sci. Technol. 49, 9930–9990.

11. Liu, C., Li, Y., Lin, D., Hsu, P.C., Liu, B., Yan, G., Wu, T., Cui, Y., and Chu, S. (2020). Lithium extraction from seawater through pulsed electrochemical intercalation. Joule 4, 1459–1469.

12. Liu, C., Hsu, P.C., Xie, J., Zhao, J., Wu, T., Wang, H., Liu, W., Zhang, J., Chu, S., and Cui, Y. (2017). A half-wave rectified alternating current electrochemical method for uranium extraction from seawater. Nat. Energy 2, 1–8.

13. Kryiakou, V., Garagounis, I., Vorras, A., Vasileiou, E., and Stoukides, M. (2020). An electrochemical Haber-Bosch process. Joule 4, 142–158.

14. Kim, H., Yang, S., Raor, S.R., Narayanan, S., Kapustin, E.A., Furukawa, H., Umans, A.S., Yagh, O.M., and Wang, E.N. (2017). Water harvesting from air with metal-organic frameworks powered by natural sunlight. Science 356, 430–434.

15. Park, H.B., Kamcev, J., Robeson, L.M., Elimelech, M., and Freeman, B.D. (2017). Maximizing the right stuff: the trade-off between membrane permeability and selectivity. Science 356, 1138–1148.

16. Schiffer, J.Z., and Manthiram, K. (2017). Electrolytic and decarbonization of the chemical industry. Joule 1, 10–14.

17. Keith, D.W., Holmes, G., St Angelo, D., and Mutch, G.A. (2018). A process for capturing CO₂ from the atmosphere. Joule 2, 1573–1594.

18. Sabatino, F., Mehta, M., Gazzani, M., Gallucci, F., Kramer, G.J., and Van Sint Annaland, M. (2020). Evaluation of a direct air capture process combining wet scrubbing and bipolar membrane electrolysis. Ind. Eng. Chem. Res. 59, 7007–7020.

19. Shu, Q., Legrand, L., Kuntke, P., Tedesco, M., and Hamelers, H.V.M. (2020). Electrochemical regeneration of spent alkaline absorbent from direct air capture. Environ. Sci. Technol. 54, 8990–8998.

20. Diederichsen, K.M., Liu, Y., Ozbek, N., Seo, H., and Hatton, T.A. (2021). Toward solvent-free direct air capture. Environ. Sci. Technol. 55, 1174–1183.

21. Kim, K., Candeago, R., Rim, G., Raymond, D., Park, A.H.A., and Su, X. (2021). Electrochemical approaches for selective recovery of critical elements in hydrometallurgical processes of complex feedstocks. iScience 24, 102374.

22. McPherson, I., and Zhang, J. (2020). Can electrofiltration of ammonia synthesis decrease its carbon footprint? Joule 4, 12–14.

23. Kazaki, M., Mutch, G.A., Qu, L., Triantafyllou, G., and Metcalfe, I.S. (2020). Autonomous and intrinsic self-healing Al₂O₃ membrane employing highly-wetting and CO₂-selective molten salts. J. Memb. Sci. 600, 117855.

24. Chen, Y., Qiao, Q., Cao, J., Li, H., and Bian, Z. (2021). Precious metal recovery. Joule 5, 3097–3115.

25. Kim, K., Candeago, R., Rim, G., Raymond, D., Park, A.H.A., and Su, X. (2021). Electrochemical approaches for selective recovery of critical elements in hydrometallurgical processes of complex feedstocks. iScience 24, 102374.

26. McPherson, I., and Zhang, J. (2020). Can electrofiltration of ammonia synthesis decrease its carbon footprint? Joule 4, 12–14.

27. Kazaki, M., Mutch, G.A., Qu, L., Triantafyllou, G., and Metcalfe, I.S. (2020). Autonomous and intrinsic self-healing Al₂O₃ membrane employing highly-wetting and CO₂-selective molten salts. J. Memb. Sci. 600, 117855.

28. Wang, L., Dykstra, J.E., and Lin, S. (2019). Energy efficiency of capacitive deionization. Environ. Sci. Technol. 53, 3366–3378.

29. Srimuk, P., Su, X., Yoon, J., Aurbach, D., and Presser, V. (2020). Charge-transfer materials for electrochemical water desalination, ion separation and the recovery of elements. Nat. Rev. Mater. 5, 517–538.

30. Tu, Y., Wang, R., Zhang, Y., and Wang, J. (2018). Progress and expectation of atmospheric water harvesting. Joule 2, 1452–1475.

31. Qi, R., Li, D., and Zhang, L.Z. (2017). Performance investigation on polymeric electrolyte membrane-based electrochemical air dehumidification system. Appl. Energy 208, 1117–1183.

32. Thimmappa, R., Gautam, M., Bhat, Z.M., Thodika, A.R.A., Devendrachari, M.C., Mukhopadhyay, S., Dargiply, N.C., and Thotyal, M.O. (2021). An atmospheric water electrolyzer for decentralized green hydrogen production. Cell Rep. Phys. Sci. 2, 100627.

33. Kim, N., Jeon, J., Chen, R., and Su, X. (2022). Electrochemical separation of organic acids and proteins for food and biomanufacturing. Chem. Eng. Res. Des. 178, 267–288.

34. Guo, K., Wustoni, S., Koklu, A., Diaz-Galicia, E., Moser, M., Hama, A., Alqathami, A.A., Ahmad, A.N., Alhamlan, F.S., Shuaib, M., et al. (2021). Rapid single-molecule detection of COVID-19 and MERS antigens via nanobody-functionalized organic electrochemical transistors. Nat. Biomed. Eng. 5, 666–677.