

Nutrient recovery and pollutant removal during renewable fuel production: opportunities and challenges

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Stimulated by the desire to achieve a Net Zero energy economy, the demand for renewable fuels is growing rapidly. The production of toxic waste streams that accompanies the transition from fossil fuels to renewable fuels is often overlooked. These waste streams include, among others, thiols and ammonia, and benzene, toluene, and xylene (BTX). When suitable treatment technologies are available, these compounds can be converted to valuable nutrients. In this opinion article, we provide an overview of expected waste streams and their characteristics. We indicate future challenges for associated waste streams, such as the lag in developing resource recovery technologies. Furthermore, we discuss unexploited opportunities to recover valuable nutrients from these waste streams.

Renewable fuels are required to achieve a Net Zero Energy economy

In 1856, Foote discovered that elevated concentrations of carbon dioxide in the atmosphere would lead to an increase in global temperature [1]. Since then, more than 2400 Gt of carbon dioxide, originating from the combustion of natural gas, crude oil, and coal, have been emitted into the atmosphere [2]. Even though the use of fossil fuels has accelerated socioeconomic development and improved human quality of life, threats of global warming associated with the combustion of these fuels are now globally recognized [3]. These threats include, among others, rising sea levels, increasing frequency of droughts and storms, loss of biodiversity from ecosystems, endangerment of global food security, and destabilization of local communities [4–6]. To limit global warming, societies are working towards a Net Zero energy economy in which greenhouse gas emissions are minimized and compensated [7–9]. Goals to reduce greenhouse gas emissions have been established across nations and have already resulted in, for example, stabilizing carbon dioxide emissions in Europe and the Americas [2,9]. To achieve Net Zero, utilization of the earth reserves of fossil fuels should be minimized and supplemented by carbon capture projects, such as reforestation [2,10–12]. Additionally, reduction in carbon emissions can be facilitated through technological solutions, for example, carbon capture storage and utilization or replacing fossil fuels with alternative renewable sources for chemicals and energy, including fuels produced from biomass (biofuels) and other renewable fuels, such as hydrogen from electrolysis.

To ensure that global warming is kept below 1.5°C, renewable energy should account for 38% of the global energy consumption by 2030 [10]. As of 2019, the global share of renewable energy accounted for 17%. The increased deployment of solar and wind energy are essential to achieve these goals. Despite being crucial for the energy transition, these technologies have several limitations, such as seasonal availability, energy storage, and differences between household

Highlights

The transition from fossil fuel to renewable fuels will be accompanied by the production of new waste streams.

Valuable nutrients, such as sulfur and nitrogen, should be recovered from polluting renewable fuel production waste streams.

New technologies need to be developed to achieve pollutant removal and nutrient recovery.

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energy consumption. First, production can be hampered because solar and wind power can vary throughout the seasons. In addition to seasonal variation, they can also vary throughout the day, causing electricity to be produced intermittently and, therefore, requiring robust storage and distribution technologies. Lastly, while being great harvesting methods for electricity, most energy consumption utilizes nonelectrical forms of power. In 2020, the consumption of electrical energy accounted for <18% of the total energy consumed in Europe [13]. Even though many more industries can be transitioned to electricity-based operations and focus on electrification, there will still be a demand for energy-dense molecule-based fuels [13].

Among the sectors that are heavily dependent on fossil fuels are transportation and aviation. In these industries, alternative energy carriers are already implemented to a certain extent, including battery technology for electrical energy, liquified hydrogen, and alcohols [13–15]. Electrical energy, utilizing battery technology, is suitable for personal mobility due to the short distances traveled and limited freight requirements. However, battery technology struggles to meet the demands for long-distance transportation (boats and unelectrified trains), nonroad machinery (construction and agriculture), and the aviation industry in the foreseeable future since the energy density in battery technology must increase tenfold to accommodate these uses [13,16]. The use of liquified hydrogen will likely not fully accommodate the requirements for long-distance heavy freight transportation either, due to its lower energy density compared with fossil fuels. Therefore, it is expected that alternative, renewable, energy-dense energy carriers will remain crucial. Potential energy carriers include, among others, methane, syngas, alcohol, and biodiesel.

The global biofuel supply has been gradually increasing over the past 30 years (Figure 1) and should quadruplicate by 2030 according to the Net Zero scenario of the International Energy Agency (IEA) [17,18]. In this scenario, 64% of the renewable energy demand for the transport sector should originate from biofuels [17]. However, one major challenge to producing these renewable carbon-based energy carriers is the formation of various waste streams containing ammonia, volatile organosulfur compounds (VOSCs), and volatile organic compounds (VOCs), such as BTX.

Waste streams generated in renewable fuel production processes

Energy-dense renewable (bio)fuels are produced from, for example, biobased materials, such as nonfood crops, plant residues, algae, pyrolyzed (bio)plastic, or other organic waste streams [19,20]. In renewable fuel refineries, these organic substrates are converted into energy-dense molecules, including methane, ethane, alcohols, diesel, kerosine, and naphtha [21,22]. Production

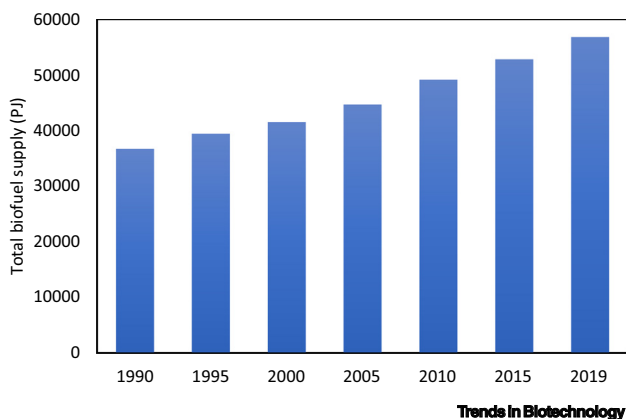


Figure 1. World biofuel supply in petajoule (PJ) between 1990 and 2019. Source: IEA (2022) World Energy Statistics and Balances [20].

of these renewable fuels requires advanced technological processes [23]. Examples of growing technologies to produce renewable fuels are gasification of organic carbon (syngas) and hydro-processed esters and fatty acids (HEFA). Syngas, a mixture of hydrogen, carbon monoxide, and carbon dioxide, is thermochemically produced via gasification of organic carbon and serves as an intermediate for other fuels, such as methanol, ethanol, and diesel fuel, which can be produced with the Fischer–Tropsch process [24–26]. The HEFA process produces, for example, biodiesel and sustainable aviation fuel (SAF) via catalytic hydrogenation of fatty organic substrates (i.e., treatment with hydrogen and a catalyst) [27]. In each of these processes, undesired byproducts, including ammonia, VOSCs and BTX, are formed. These byproducts need to be removed from the product stream because, for example, the concentration of sulfur in gas engine fuels should be below 35.5 ppm [22]. A simplified process scheme of renewable (bio)fuel production processes and the formed byproducts is presented in Figure 2.

Various technologies can be used to separate the byproducts from renewable fuel production, resulting in multiple liquid and gaseous waste streams. Ammonia and hydrogen sulfide can be adsorbed into a caustic solution and separated from the gas stream. VOSCs and BTX are present in the gas phase together with carbon dioxide and hydrogen sulfide. High levels of ammonia, VOSCs, and BTX can also be found in traditional fossil fuel refinery processes. They are typically destructed in the Claus process, classically used to desulfurize gaseous waste streams. However, the Claus process is not suitable as a sulfur recovery unit (SRU) due to the decentralized nature of renewable fuel production and specific quantities of hydrogen sulfide produced.

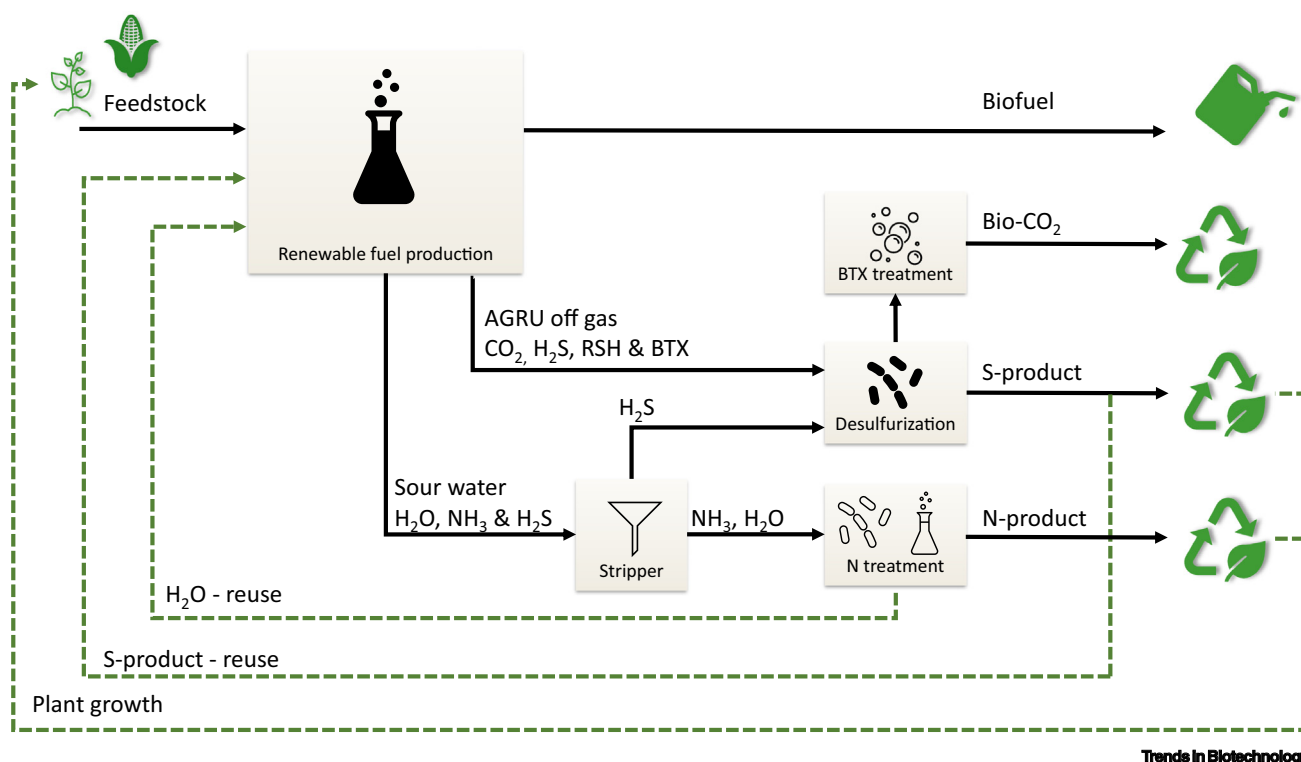


Figure 2. Simplified process scheme of renewable (bio)fuel production processes and the byproducts formed. Organic feedstock is converted to renewable (bio)fuel. In this process, sour water, containing ammonia (NH_3) and hydrogen sulfide (H_2S), and acid gas, containing carbon dioxide, sulfide, thiols (RSH), and aromatic hydrocarbons, such as benzene, toluene, and xylene (BTX) are produced. Acid gas is obtained in the acid gas removal unit (AGRU). These two waste streams need to be treated to recover valuable products. Abbreviations: N, nitrogen; S, sulfur.

Therefore, different technologies need to be implemented to recover sulfur. These alternative technologies typically do not destroy contaminants, such as ammonia, VOSCs, and VOCs, and the presence of such contaminants can even disrupt the efficiency of alternative desulfurization processes. Thus, there is a need to develop technologies that can prevent emission of contaminants while also recovering them in the form of a valuable resource. This circular process will further reduce the carbon footprint of the production of renewable fuels.

Examples of hydrogen sulfide, VOSCs, ammonia and BTX formed during the production of different renewable fuel products are presented in Table 1. The values provided are indicative and are strongly influenced by the feedstock [28,29], process conditions, and the catalyst used. The latter influences the amount of VOSCs produced [30–32] and its performance is dependent on metal–sulfur bonds. To maintain catalytic activity, a continuous supply of hydrogen sulfide is required in the process [28,31]. As a result, hydrolyzed sulfur (e.g. hydrogen sulfide) leaves the process. As the catalyst ages, its selectivity and activity decrease, inevitably leading to a shift in the equilibrium in the hydrotreater. As a result, incomplete hydrolysis of sulfur compounds leads to the formation of VOSCs [30,31,33,34].

The need for renewable fuel waste stream treatment and resource recovery

Ammonia

Nitrogen is an essential nutrient and forms a large fraction of organic material. Carbon:nitrogen ratios in crops can be up to 0.15 and are highly dependent on plant variety and nutrient availability [35]. When producing renewable fuels from crops and biobased waste, the available nitrogen is converted to ammonia, which is the most reduced form of nitrogen. Although ammonia is a readily available substrate and is used in many fertilizers [36,37], it also can cause issues when released into the environment. It is a corrosive, irritating gas that can lead to serious lung burns when inhaled. In addition, ammonia in the atmosphere reduces the air quality and depletes the ozone in the stratosphere [38]. On land, ammonia depositions result in the acidification and eutrophication of soils, which eventually result in the loss of biodiversity [39]. Furthermore, ammonia is highly soluble in water. The disposal of large quantities of ammonia in water bodies result in algal blooms, eutrophication, and oxygen depletion, leading to fish mortality and overall loss of ecosystems [38]. Therefore, ammonia should be removed from waste streams before they are released into the environment. In addition to harming the environment, the presence of ammonia in, for example, the Fischer–Tropsch process is unwanted because it poisons catalysts that are used to upgrade

Table 1. Examples of renewable fuels and their waste stream composition^a

Fuel	H ₂ (%)	CH ₄ (%)	CO ₂ (%)	CO (%)	H ₂ S (ppm _v)	VOSC (ppm _v) ^b	BTX (ppm _v)	NH ₃ (%)	Refs
Biogas agriculture		53–57	39–43		2–1000	0.1–10	0.43	3–7 ppm _v	[63,64]
Biogas landfill ^c		48	47		5.8	4.8	2.25		[64]
Syngas	25–42	0–12	1–32	5–57	0.06–15 300	0.15–600	20–8000	0–2	[65–67] ^{d,e}
AGRU off-gas	<1	<1	40–95	<1	0.5–50	0–100	0–500	<0.01	d
SWS off-gas	<1	<1	<1	<1	30–70%		0–100		d
Alcohol from syngas					1.2 ^f	4–18 ^f	20–200 ^f	<0.15 ^g	[30,33,34]

^aAbbreviations: AGRU, acid gas removal unit; SWS, sour water stripper.

^bIncluding C₁–C₄ thiols.

^cLandfill containing municipal waste, animal bedding, and food waste.

^dB.V. Paquell, personal communication (2022).

^e<https://netl.doe.gov/research/coal/energy-systems/gasification/gasifipedia/syngas-composition>.

^fIn liquid product.

^gNH₄ in aqueous Fischer–Tropsch product with 40 PPM_v NH₃ in the syngas feed.

syngas to longer hydrocarbon fuels [40]. While ammonia can be converted to nitrogen gas in conventional treatment technologies, a more circular process can be achieved if ammonia is recovered directly. Recovered ammonia can be used as a resource for agriculture, chemical industries, or as energy carrier [41].

The recovery of ammonia from low-concentrated waste streams, such as in wastewater treatment plants, is limited. Here, ammonia is removed rather than recovered. In wastewater treatment plants, oxygen is typically used to oxidize ammonia to inert nitrogen gas [42]. This process requires a high energy input, and nitrogen fertilizers are simultaneously produced from atmospheric nitrogen gas via the energy-intensive Haber–Bosch process [43]. Utilizing the ammonia-rich waste stream (20–50%) directly from a renewable fuel production plant would result in tremendous energy savings and may be economically attractive for these types of waste streams. Various technologies are under development for ammonia recovery, including electrochemical treatment, stripping, zeolites, and production of struvite, among others. [44]. However, implementation of these technologies remains limited [44,45]. The applicability of these technologies for this type of waste streams should be further evaluated so that ammonia can become a valuable byproduct rather than a costly waste stream in the renewable fuel production process.

Organosulfur compounds

One major underexposed challenge arising from renewable fuel production is the formation and/or presence of VOSCs. These compounds, also called thiols, are hazardous and toxic at low concentrations because they inhibit the respiratory system and are highly corrosive [46]. Apart from their toxicity, these highly volatile compounds have a foul odor and, combined with their very low odor thresholds, can have severe effects at low concentrations [47]. Upon combustion of (bio) fuels, VOSCs form sulfur dioxide, which contributes to the formation of acid rain and dry acid deposition [48]. Therefore, it is important that these VOSCs are removed from both product and waste streams.

Currently, fossil fuel extraction and refining are major sources of anthropogenic VOSCs [49]. Treatment technologies for VOSCs at extraction and refinery sites are optimized for processing streams from the oil and gas markets. These streams have stable process-specific compositions, high volumetric flow rates and contain vast amounts of hydrogen sulfide and VOSCs. By contrast, streams produced in renewable fuel-production facilities have more decentralized characteristics with a fluctuating VOSCs content. The available technologies for large scale oil and gas industries may not be suitable to treat the VOSC-containing waste streams from renewable fuel production because of the fluctuating VOSC content and lower loading rates. Typically, low loads of VOSCs (200 kg S/d) are removed by sorption processes, which produce large amounts of toxic waste and have limited options for sulfur recovery. Additionally, the composition of the waste streams differ and conventional technologies are not able to achieve sufficient removal in renewable fuel production plants and meet the desired product specifications for the final fuel product. Currently, no technology is available to accommodate the removal and conversion of VOSCs required for Net Zero goals.

Besides removal and conversion of VOSCs, sulfur recovery will become increasingly important in the Net Zero energy economy [50]. The current sulfur market is dominated by sulfur production from fossil fuels. For example, 93% of the total elemental sulfur produced in the USA in 2019 came from fossil fuelsⁱⁱ. Most elemental sulfur produced worldwide is used for the production of sulfuric acid to extract phosphate ores [51]. The obtained phosphate and elemental sulfur are both essential in agricultural activities. Therefore, to secure food production in the future, recovery of elemental sulfur and phosphate will be crucial in a Net Zero energy economy.

BTX

BTX are present in natural gas and crude oil and, additionally, are formed during the refining process. In renewable fuel production processes, the high temperature conversion of biomass also results in BTX formation [52,53]. In the chemical industry, these compounds are often used as solvents in, for example, paint, thinners, cosmetics, and pharmaceuticals [54]. Despite such frequent use, they are toxic compounds that act as carcinogens or neurotoxins in humans and are harmful to aquatic life [54,55]. In addition, although these compounds are biodegradable, they persist in the environment [55,56]. Therefore, stringent emission limits are implemented in many countries and the presence of these compounds is strictly monitored in drinking water, with limits as low as 0.5 ppb [57,58]. To prevent environmental damage caused by these undesired byproducts, emissions should be avoided, and BTX should be captured and detoxified in an efficient manner.

There are various technologies to treat BTX compounds, including filtration and adsorption to activated carbon and zeolites, combustion, condensation, or various forms of bioremediation [54,59]. Chemical treatment methods require high capital investment along with high operational and maintenance costs, while achieving limited removal efficiencies [54,60]. Waste streams containing BTX from traditional fossil fuel plants are typically combusted in the Claus process (S. Ibrahim, PhD thesis, University of Maryland, College Park, 2015). However, this requires additional fuel input. *In situ* bioremediation of polluted environments, in which BTX compounds are converted to carbon dioxide, methane, and water, is preferred over *ex situ* treatment due to lower costs and higher efficiencies [59]. Additionally, bioremediation produces useful byproducts, such as methane and carbon dioxide. Methane can be used as an energy carrier, whereas the carbon dioxide can be utilized in carbon capture or power to gas applications, producing more renewable fuel. However, these remediation technologies are relatively slow anaerobic processes focused on low-concentration sites (e.g., contaminated aquifers), with concentrations ranging from 2 µg/l to 25 mg/l [55,61]. By comparison, in renewable fuel production processes, gaseous waste BTX can be concentrated up to 500 ppm_v (B.V. Paqell, personal communication, 2022). Therefore, increased removal rates are desired to treat renewable fuel waste streams. Aerobic biodegradation requires vast amounts of oxygen [62], but could be further explored for remediation of the highly concentrated waste streams obtained in renewable fuel production.

Concluding remarks

The production of biobased chemicals and energy-dense energy carriers, such as biodiesel and ethanol, will be an important step in the transition toward a Net Zero energy economy. However, production of these renewable fuels will be accompanied by the production of hazardous and potentially toxic waste streams, such as VOCs, BTX, and ammonia, if left untreated. These waste streams contain valuable molecules and can be utilized in a biobased Net Zero energy economy, with the aim of closing not only carbon, but also nutrient (nitrogen and sulfur) cycles. To achieve this valorization of waste streams by nutrient recovery and reuse, new technologies need to be developed and implemented.

Production technologies for renewable fuels are under constant development. However, waste production depends on the biomass source and production technology. The renewable fuel market is expanding and developing rapidly, and the final contribution of each process based on size, technology, and feed stock composition is hard to predict. Increased production efficiencies may result in lower VOSC formation from the catalyst and less loss of valuable organic compounds in the form of BTX. The composition of the produced waste streams may also change once the renewable fuel production process is improved. However, sulfur and nitrogen are present in most organic feed stocks and need to be removed from the product to avoid the formation of nitric oxide, nitrogen dioxide, and sulfur dioxide upon combustion.

Outstanding questions

What are the specific characteristics and quantities of waste streams that are produced in renewable fuel refineries? Based on these characteristics, which technologies are most suited to treat these waste streams? Furthermore, which technologies are lacking and need to be developed?

To achieve Net Zero, a shift is required from a linear to a circular economy. How can effluent waste streams be treated to achieve recovery rather than removal? Which (combination of) technologies need to be developed to achieve the desired recovery?

What is the sustainability of renewable fuel production when including new recovery technologies? How can lifecycle sustainability assessments map the impact of renewable fuel production?

What is the best technology for resource recovery, based on a techno-economic analysis?

How can policy makers gain a complete overview of the most pressing issues and challenges associated with renewable fuel production now and in the future?

If the waste streams produced during renewable fuel production are left untreated, valuable resources will go to waste. More importantly, when attempting to solve the global carbon emission crisis, we should avoid creating the next environmental problem of pollution and waste production. Environmental and economic impacts of different pollutant removal and resource recovery technology need to be considered (see [Outstanding questions](#)). Therefore, an integral approach, acknowledging all aspects of the renewable fuel production process in the transition from fossil to renewable fuel, is of utmost importance.

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Declaration of interests

None are declared by the authors.

Resources

ⁱ<https://ourworldindata.org/fossil-fuels>

ⁱⁱwww.usgs.gov/Centers/Nmic/Sulfur-Statistics-and-Information

References

1. Foote, E. (1856) Circumstances affecting the heat of the sun's rays. *Am. J. Sci. Arts* 22, 382–383
2. IPCC (2022) Climate Change 2022: Mitigation of Climate Change. In *Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, Cambridge University Press
3. Aykut, S.C. and Castro, M. (2017) The end of fossil fuels? Understanding the partial climatization of global energy debates. In *Globalising the Climate* (Aykut, S. et al., eds), pp. 173–193, Taylor & Francis
4. El Bilali, H. et al. (2020) Climate change and food security. *Agric. Forestry* 66, 197–210
5. Sinay, L. and Carter, R.W. (2020) Climate change adaptation options for coastal communities and local governments. *Climate* 8, 7
6. IPCC (2022) Climate Change 2022: Impacts, Adaptation, and Vulnerability. In *Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, Cambridge University Press
7. Gaulin, N. and Le Billon, P. (2020) Climate change and fossil fuel production cuts: assessing global supply-side constraints and policy implications. *Clim. Pol.* 20, 888–901
8. German Advisory Council On Global Change (2014) *World in Transition 3: Towards Sustainable Energy Systems*, Routledge
9. United Nations/Framework Convention on Climate Change (2015) *Adoption of the Paris Agreement, 21st Conference of the Parties*, United Nations
10. IRENA (2022) *World Energy Transitions Outlook 2022: 1.5°C Pathway*, International Renewable Energy Agency
11. Woolf, D. et al. (2018) Biochar for climate change mitigation: navigating from science to evidence-based policy. In *Soil and Climate* (Lal, R. and Stewart, B.A., eds), pp. 219–248, CRC Press
12. Lehmann, J. et al. (2021) Biochar in climate change mitigation. *Nat. Geosci.* 14, 883–892
13. Mertens, J. et al. (2020) Why the carbon-neutral energy transition will imply the use of lots of carbon. *J. Carbon Res.* 6, 39
14. Staffell, I. et al. (2019) The role of hydrogen and fuel cells in the global energy system. *Energy Environ. Sci.* 12, 463–491
15. Allegue, L.B. et al. (2012) *BioGas and Bio-Syngas Upgrading*, Danish Technological Institute
16. Wisell, T. et al. (2018) *Fuel and Technology Alternatives in Non-Road Engines*, IEA-AMF
17. IEA (2011) *Technology Roadmap - Biofuels for Transport*, IEA
18. IEA (2022) *Global Biofuel Demand in the Net Zero Scenario, 2015-2030*, IEA
19. De Vrieze, J. et al. (2020) The hydrogen gas bio-based economy and the production of renewable building block chemicals, food and energy. *New Biotechnol.* 55, 12–18
20. Miandad, R. et al. (2019) Catalytic pyrolysis of plastic waste: moving toward pyrolysis based biorefineries. *Front. Energy Res.* 7, 27
21. Cherubini, F. (2010) The biorefinery concept: using biomass instead of oil for producing energy and chemicals. *Energy Convers. Manag.* 51, 1412–1421
22. Roddy, D.J. (2013) A syngas network for reducing industrial carbon footprint and energy use. *Appl. Therm. Eng.* 53, 299–304
23. Math, M.C. et al. (2010) Technologies for biodiesel production from used cooking oil — a review. *Energy Sustain. Dev.* 14, 339–345
24. Boemigter, H. et al. (2002) Green diesel from biomass by Fischer-Tropsch synthesis: new insights in glass cleaning and process design. In *A.V. Bridgewater, Pyrolysis and Gasification of Biomass and Waste*, pp. 4–7, Proceedings of PGBW Expert Meeting, Strasbourg, France
25. Stoll, I.K. et al. (2020) Syngas fermentation to alcohols: reactor technology and application perspective. *Chem. Ing. Tech.* 92, 125–136
26. Xu, D. et al. (2011) The effects of syngas impurities on syngas fermentation to liquid fuels. *Biomass Bioenergy* 35, 2690–2696
27. Shahriar, M.F. and Khanal, A. (2022) The current techno-economic, environmental, policy status and perspectives of sustainable aviation fuel (SAF). *Fuel* 325, 124905
28. McCue, A.J. and Anderson, J.A. (2014) Sulfur as a catalyst promoter or selectivity modifier in heterogeneous catalysis. *Catal. Sci. Technol.* 4, 272–294
29. Sanford, S.D. et al. (2009) Feedstock and biodiesel characteristics report. *Renew. Energy Group* 416, 1–136
30. Christensen, J.M. et al. (2009) Effects of H₂S and process conditions in the synthesis of mixed alcohols from syngas over alkali promoted cobalt-molybdenum sulfide. *Appl. Catal. A Gen.* 366, 29–43
31. Malins, K. (2021) Synthesis of renewable hydrocarbons from vegetable oil feedstock by hydrotreatment over selective sulfur-free SiO₂-Al₂O₃ supported monometallic Pd, Pt, Ru, Ni, Mo and bimetallic NiMo catalysts. *Fuel* 285, 119129
32. Abraham, V. and deMan, J.M. (1987) Effect of some isothiocyanates on the hydrogenation of canola oil. *J. Am. Oil Chem. Soc.* 64, 855–858
33. Hensley, J.E. et al. (2013) Compositional analysis and advanced distillation curve for mixed alcohols produced via syngas on a K-CoMoSx catalyst. *Energy Fuels* 27, 3246–3260

34. Andersson, R. *et al.* (2014) Higher alcohols from syngas using a K/Ni/MoS₂ catalyst: trace sulfur in the product and effect of H₂S-containing feed. *Fuel* 115, 544–550
35. Popovic, M. and Minceva, M. (2021) Standard thermodynamic properties, biosynthesis rates, and the driving force of growth of five agricultural plants. *Front. Plant Sci.* 12, 871
36. Eriksson, J.E. (1990) Effects of nitrogen-containing fertilizers on solubility and plant uptake of cadmium. *Water Air Soil Pollut.* 49, 355–368
37. Dimkpa, C.O. *et al.* (2020) Development of fertilizers for enhanced nitrogen use efficiency – trends and perspectives. *Sci. Total Environ.* 731, 139113
38. Miller, S.A. *et al.* (2007) Environmental trade-offs of biobased production. *Environ. Sci. Technol.* 41, 5176–5182
39. Guthrie, S. *et al.* (2018) *The Impact of Ammonia Emissions from Agriculture on Biodiversity*, RAND Corporation and The Royal Society
40. Ma, W. *et al.* (2015) Fischer-Tropsch synthesis: effect of ammonia in syngas on the Fischer-Tropsch synthesis performance of a precipitated iron catalyst. *J. Catal.* 326, 149–160
41. Tawalbeh, M. *et al.* (2022) Ammonia: a versatile candidate for the use in energy storage systems. *Renew. Energy* 194, 955–977
42. Metcalf, L. *et al.* (2004) *Wastewater Energy: Treatment and Reuse*, McGraw-Hill
43. Erisman, J.W. *et al.* (2008) How a century of ammonia synthesis changed the world. *Nat. Geosci.* 1, 636–639
44. Beckinghausen, A. *et al.* (2020) From removal to recovery: an evaluation of nitrogen recovery techniques from wastewater. *Appl. Energy* 263, 114616
45. Morlanés, N. *et al.* (2021) A technological roadmap to the ammonia energy economy: current state and missing technologies. *Chem. Eng. J.* 408, 127310
46. National Research Council (2013) *Acute Exposure Guideline Levels for Selected Airborne Chemicals*, The National Academies Press
47. Ruth, J.H. (1986) Odor thresholds and irritation levels of several chemical substances: a review. *Am. Ind. Hyg. Assoc. J.* 47, A142–A151
48. Rokni, E. *et al.* (2015) Reduction of sulfur dioxide emissions by burning coal blends. *J. Energy Resour. Technol.* 138, 032204
49. Salih, Y.M. *et al.* (2018) A comparative study of the emission of volatile organic compounds (VOCs) from different sulfur content crude oils. *Pet. Sci. Technol.* 36, 1037–1043
50. Maslin, M. *et al.* (2022) Sulfur: a potential resource crisis that could stifle green technology and threaten food security as the world decarbonises. *Geogr. J.* 188, 498–505
51. Kelly, T.D. *et al.* (2010) *Historical statistics for mineral and material commodities in the United States*. US Geological Survey Data Series 140 pp. 01–006
52. Wang, W. *et al.* (2018) Catalytic fast pyrolysis of cellulose for increasing contents of furans and aromatics in biofuel production. *J. Anal. Appl. Pyrolysis* 131, 93–100
53. Mo, W. *et al.* (2022) Processes simulation and environmental evaluation of biofuel production via Co-pyrolysis of tropical agricultural waste. *Energy* 242, 123016
54. El-Naas, M.H. *et al.* (2014) Aerobic biodegradation of BTEX: progresses and prospects. *J. Environ. Chem. Eng.* 2, 1104–1122
55. Lueders, T. (2017) The ecology of anaerobic degraders of BTEX hydrocarbons in aquifers. *FEMS Microbiol. Ecol.* 93, 1–13
56. Oh, Y.-S. *et al.* (1994) Interactions between benzene, toluene, and p-xylene (BTX) during their biodegradation. *Biotechnol. Bioeng.* 44, 533–538
57. European Council (2020) *Directive (EU) 2020/2184 of the European Parliament and of the Council of 16 December 2020 on the Quality of Water Intended For Human Consumption*, European Council
58. US Environmental Protection Agency (2006) *2006 Edition of the Drinking Water Standards and Health Advisories*, US Environmental Protection Agency
59. Farhadian, M. *et al.* (2008) In situ bioremediation of monoaromatic pollutants in groundwater: a review. *Bioresour. Technol.* 99, 5296–5308
60. Varjani, S.J. (2017) Microbial degradation of petroleum hydrocarbons. *Bioresour. Technol.* 223, 277–286
61. Logeshwaran, P. *et al.* (2018) Petroleum hydrocarbons (PH) in groundwater aquifers: an overview of environmental fate, toxicity, microbial degradation and risk-based remediation approaches. *Environ. Technol. Innov.* 10, 175–193
62. Hatipoğlu-Bağcı, Z. and Motz, L.H. (2019) Methods for investigation of natural attenuation and modeling of petroleum hydrocarbon contamination in coastal aquifers. *Jeoloji Muhendisligi Dergisi* 43, 131–154
63. Calbry-Muzyka, A. *et al.* (2022) Biogas composition from agricultural sources and organic fraction of municipal solid waste. *Renew. Energy* 181, 1000–1007
64. Li, Y. *et al.* (2019) Composition and toxicity of biogas produced from different feedstocks in California. *Environ. Sci. Technol.* 53, 11569–11579
65. Hgman, C. and van der Burgt, M. (2003) *Gasification*, Elsevier
66. Supp, E. (1990) *How to Produce Methanol from Coal*, Springer
67. Liakakou, E.T. *et al.* (2021) Connecting gasification with syngas fermentation: comparison of the performance of lignin and beech wood. *Fuel* 290, 120054