

ORIGINAL RESEARCH

Building the bioeconomy: A targeted assessment approach to identifying biobased technologies, challenges and opportunities

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Abstract

The authors explore opportunities, challenges, and strategies to translate and responsibly scale innovative biobased technologies to build more sustainable bioeconomies. The pandemic and other recent disruptions increased exposure to issues of resilience and regional imbalance, highlighting a need for production and consumption regimes centred more on local biobased resources and dispersed production. The authors review potential biobased technology strategies and identify promising and feasible options for the United Kingdom. Initial landscape and bibliometric analysis identified 50 potential existing and emerging biobased technologies, which were assessed for their ability to fulfil requirements related to biobased production, national applicability, and economic-, societal-, and environmental-benefits, leading to identification of 18 promising biobased production technologies. Further analysis and focus-group discussion with industrial, governmental, academic, agricultural, and social stakeholders, identified three technology clusters for targeted assessment, drawing on cellulose-, lignin-, and seaweed feedstocks. Case studies were developed for each cluster, addressing conversations around sustainable management, use of biomass feedstocks, and associated environmental-, social-, and economic challenges. Cases are presented with discussion of insights and implications for policy. The approach presented is put forward as a scalable assessment method that can be useful in prompting, informing, and advancing discussion and deliberation on opportunities and challenges for biobased transformations.

KEY WORDS

bio-economy, industry, responsible research innovation, scale-up strategies, synthetic biology

1 | INTRODUCTION

Transitioning to bioeconomy systems built on renewable inputs and circular resource streams [1] is a multi-level challenge, requiring shifts in production as well as consumption patterns and involving not only high-level policy changes but also meso- and micro-changes in technologies, management systems, and business and governance models. Countries (and regions) will need customisation to their circumstances. In the case of the United Kingdom (UK), as we subsequently discuss, we suggest that there is a realistic vision of future manufacturing that involves supply chains that are substantially less fossil-fuel dependent and more distributed and resilient, relying

significantly on biobased and sustainable native resources adapted to local industrial contexts, resources, and biodiversity. Achieving this prospect would be aided by the adoption of innovative biobased technologies for the synthesis and manufacture of chemicals and materials (biomanufacturing), and for applications in agriculture and energy. Yet, while promising, there are significant operational challenges to developing viable and scalable pathways and strategies for biomanufacturing and other biobased production strategies. These challenges include applicability to regional conditions, technical feasibility, regulatory constraints, economic, societal, and environmental sustainability aspects, stakeholder acceptance, and associated path dependency, institutional, and policy issues.

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This paper explores opportunities, challenges, and strategies to translate and responsibly scale innovative biobased technologies to build a sustainable bioeconomy. The European Commission (EC) describes the bioeconomy as the production of renewable biological resources and the conversion of these resources, and their resultant waste streams, into value-added products, such as food, feed, biobased products, and bio-energy [1]. In this paper, we demonstrate how a rapid targeted assessment method can provide insights about how the adoption of models based on biotechnologies can address responsible and sustainable bioeconomy development, including anticipation of potential roadblocks to implementation and possible resolutions to overcome these. We proceed by first reviewing the contextual framework for considering bioeconomy development, including environmental, economic and societal aspects, with attention to the UK bioeconomy. This is followed by consideration of the approach and methods used to undertake the targeted assessment, presentation of results, discussion of implications and policy insights, and conclusion and limitations.

1.1 | Environment, economy, society, and the bioeconomy

The detrimental effects of fossil fuels on the environment and climate change are well documented; CO₂ emissions from fossil fuels are reported to contribute to 89% of all emissions [2]. Recognition and societal concern about unsustainability of the continued long-term economic dependence on coal, natural gas, and oil has increased [3, 4]. Yet, while awareness has risen, adopting sustainable solutions has proven difficult. The piecemeal progress made globally has been further impacted in recent years by the COVID-19 pandemic and rising international conflicts, exacerbating the challenges of achieving targets for net zero greenhouse gas (GHG) emissions and sustainable development goals [5–8].

The reduction of GHGs can be aided by measures such as carbon capture or by changes in mobility and other consumption patterns. However, deeper sustainability transitions necessitate the implementation of rigorous and consistent bioeconomic strategies, including the adoption of innovative biotechnologies [9, 10]. Yet, progress here is slow. The present economic size of the bioeconomy depends on definitions used. Estimates using European Union bioeconomy designations indicate that the bioeconomy has maintained a share of about one-tenth of Europe's (EU-27) economy as reported in 2012 [1] through to 2017 [11]. In other words, while there are some country variations, bioeconomy transition is still at an early stage at best. Nonetheless, there continues to be policy ambition to accelerate sustainable growth throughout the bioeconomic value chain—from feedstocks to bioproducts—through the production of renewable biobased resources and the conversion of waste streams into value-added products.

One of the underlying challenges to bioeconomy development is environmental regulation that demands a disproportionately high environmental standard for biobased

products compared to their fossil fuel-based counterparts. For example, mandatory ecological sustainability provisions, outlined in both the 2009 EU Renewable Energy Directive (2009/28/EC) [12] and the EU Fuel Quality Directive (2009/30/EC) [13], stipulate that biofuel, produced from biomass, must produce at least 35% less GHG compared to fossil fuels. In 2017, this became at least 50%, and it continues to rise [14] limiting the potential of available biomass and allowing fossil fuel usage to persist uncontested. The evolution of a competitive and sustainable bioeconomy requires significant and enduring public investment in both research and innovation, and the establishment of a pro-active regulatory framework that incentivises private sector investment in the development and commercialisation of new biobased products [15].

At the same time, it is often assumed that sustainability and ‘green-ness’ are inherent to, and inevitable products of, the bioeconomy [4]. Multiple criteria and indicators for a sustainable bioeconomy have been developed [16, 17] but an internationally agreed set of criteria for a sustainable bioeconomy still does not exist. Moreover, the sustainability of bio-production is not automatically guaranteed. Environmental trade-offs can be required as bioproduction seeks industrial viability (e.g. water usage, habitat destruction, or energy requirements). Environmental repercussions may be heightened if the bioeconomy is developed in isolated ways and in the narrow pursuit of scale and competitive advantage in conditions of growing resource scarcity and demand [18].

Among other major problems currently faced in bioeconomy development are the geographical availability of suitable bioresources, protection of bioresources from environmental and mechanical damage, reliability of supply, and the complex nature of natural fibres, that is, differences in consistency, quality, and usability of resources. Although, renewable feedstocks can be produced indefinitely at a certain level, they are still exhaustible if the rate of extraction is faster than the rate of regeneration [19]. It has been contended that a bioeconomy producing products at a high enough level to fulfil demand could be unsustainable, with fears that this would result in an accelerated rate of depletion of natural resources (water, nitrogen, phosphorus etc.), land use competition with food production, increased eutrophication, and loss of biodiversity through the exploitation of marginal land (grassland, peatland, wetland etc.) and forests for agriculture [20–26]. We anticipate that such challenges may be more readily overcome by developing supply chains that are more distributed and resilient, relying on biobased and sustainable native resources. For these resources to be sustainably managed and preserve biodiversity, bio-based production ideally needs to be locally managed using viable local resources.

While the bioeconomy has the potential to ‘green’ the economy, the mode of its implementation is paramount to the ultimate success (or failure) on this front. There are two envisaged trajectories for development of the bioeconomy. The first is a delimiting path, involving integration of the bioeconomy into the current economic model where a limited number of actors narrowly define problems and solutions. This

would likely produce a bioeconomic model overlain with green claims and where economic output is prioritised over social and environmental impact. A contrasting development strategy, which is the approach that we pursue, is one that is sustainability-centric, incorporating diverse stakeholder and expert input and encouraging multiple solutions [27]. This would require influencing micro-economic behaviour and processes to embed production-consumption chains that are more distributed and resilient [28, 29] as well as the development of complex networks of viable businesses—including small and mid-size enterprises (SMEs), and economic activities that use ecological resources in sustainable, diverse and efficient ways, prioritising a circular economy model.

Such holistic approaches to the bioeconomy view it as a comprehensive social transition that utilises new biological knowledge for commercial and industrial purposes, and to improve human welfare [30]. While social inclusiveness and acceptance are important precursors to the development of a successful bioeconomy strategy, implementation to date has been weak. Bioeconomy sustainability assessment tools do not adequately capture social aspects [31], and social outreach often focusses on creating acceptance for priorities that have already been set rather than inclusive participation and active involvement [32].

1.2 | The UK bioeconomy context

The Climate Change Act [33] committed the UK to an 80% reduction in carbon emissions, relative to 1990, by 2050. In June 2019, this target was extended to a 100% reduction. The UK is not on track to meet either of these targets. Meanwhile, the UK's 'Bioeconomy Strategy: 2018–2030' aimed to double the impact of the UK bioeconomy from £220 billion (2014) to £440 billion by 2030 [34].

Subsequently, the global COVID-19 pandemic (early 2020 through to May 2023) disrupted many plans, with contrasting implications. On the one hand, the pandemic led to the biggest economic crisis in the UK since records began, with a fall in gross domestic product of 20.4% in the second quarter of 2020 [35]. Economic problems persisted into 2021, although with some recovery towards the latter part of the year, such that by November 2021 the UK economy had regained its pre-pandemic size [36], albeit with variations by sectors and regions and with high levels of ongoing uncertainty (complicated not only by the pandemic but also by Brexit, rising fossil fuel prices, and global disruptions). On the other hand, the pandemic intensified debate, and led to government policy announcements, about 'building back better' with growth that levels regional imbalances, fosters resilience, and transitions to net zero GHG emissions [37]. Such policies also featured in the 2021 UK Innovation Strategy [38], which superseded the 2018 UK Bioeconomy Strategy, highlighting the potential of engineering biology as an enabling technology in rebuilding the economy.

The heightened debate about more sustainable and resilient production and consumption transitions in the UK is a

significant development. Relying on requests for behavioural change by itself will be insufficient and will not enable the UK to resist future crises. Instead, structural changes in industry and the economy, solid commitment to environmental targets, and a levelling of societal imbalances are needed. In considering how a greener, redistributed recovery and transition might occur, possibilities have been raised that involve shifts to production regimes based more on local bioeconomy resources and dispersed production, and less on point-source resources (fossil fuels) and distant international sources, with customisation to local contexts, industry, and biodiversity. Innovative biological pathways for making chemicals, materials, and other bioproducts, and for applications in agriculture and energy have emerged that promise not only greater sustainability but also new functionalities. However, any shift to biobased is a multi-dimensional challenge, with issues that are not just technical and environmental but also political, economic and societal.

A key aim of this paper is to go beyond high-level pronouncements and broad statements of intent to examine more specifically which transitions to sustainable biobased production are most promising, how these transitions might occur, what challenges might arise, and how these challenges could be overcome. We take these up through developing and implementing a targeted assessment method applied to potential UK biobased production pathways.

2 | MATERIALS & METHODS

There are multiple technology assessment approaches to evaluating potential technological developments and impacts and consider policy implications, including approaches relying on extensive expert analyses and those which involve stakeholders and societal actors [39]. We pursued a simplified and low-cost approach that combined analysis of available documentation, iterative feedback, and focus group stakeholder participation. The assessment approach was targeted in that, after an initial broad scan of potential bioeconomy technologies, it concentrated analysis on a small number of selected cases of biobased production technologies. The steps in the method are described in this section and presented in Figure 1. Further details are included in the Supporting Information S1: Supplementary Materials, including search terms and selection processes. This targeted assessment method was implemented over a period from August 2020 (start of long-list generation) to April 2021 (completion of case studies).

2.1 | Assessment steps

2.1.1 | Bioeconomy to biobased production technologies: Long list to short list generation

Through landscape analysis and bibliometric searches, we developed a starting long list of extant and emerging innovative

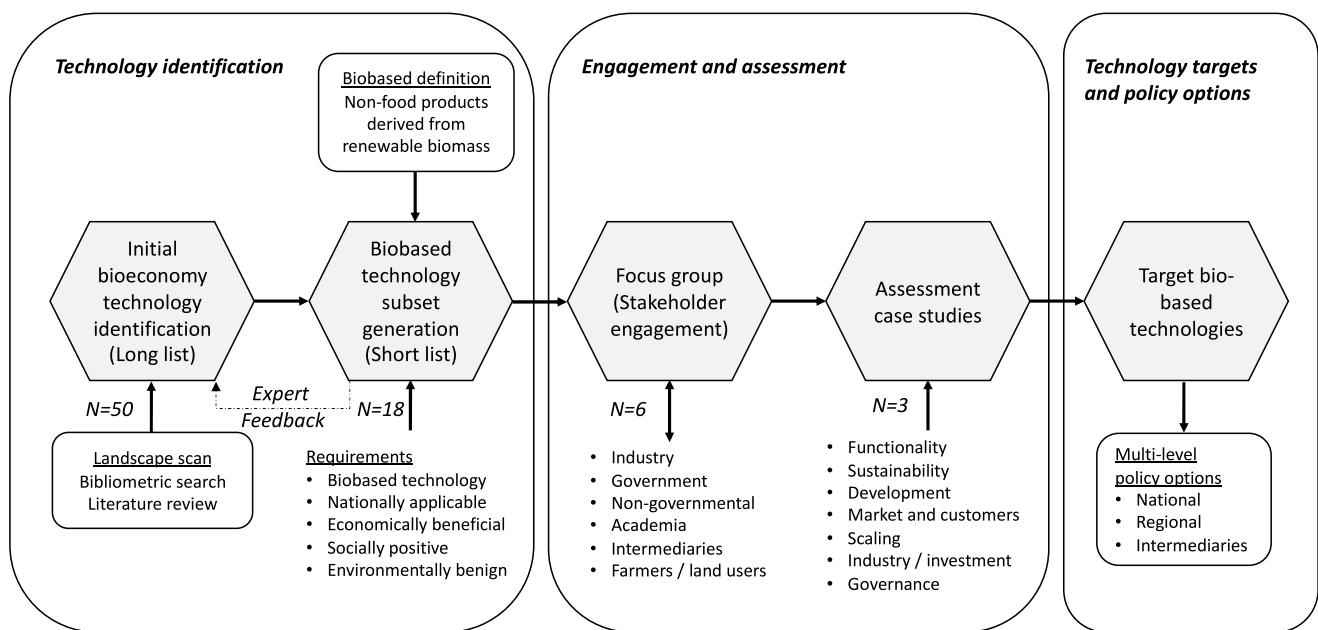


FIGURE 1 Targeted assessment approach.

technologies that could contribute to bioeconomy development. Bioeconomy technologies were broadly defined as ones that facilitated the production of goods, materials, energy, and services with the sustainable use of biological resources. We used a combination of bibliometric searches, reviews of available literature, and searches of other online resources. There was a focus on technologies that were generic (i.e. not highly company specific) and either entering or relatively close to market—that is, which could be implemented within, as a maximum, the next 5–10 years. A total of 50 potential bioeconomy technologies emerged (see Supporting Information S1: Supplementary Materials and Table S1).

To refine this initial bioeconomy set to a short list of promising biobased production technologies, we applied a definition of biobased as ‘non-food products derived from renewable biomass (plants, algae, crops, trees, marine organisms, and biological waste from households, animals and food production)’ [40]. Given the saturation of the UK market with biobased technologies for healthcare applications, only technologies pertinent to bioagricultural and bioindustrial applications were included in this study. Long list technologies were further assessed for their ability to meet requirements related to national applicability (in this case, to the UK). Criteria to assess the promise of the technology included utilisation of native feedstock, resources, and expertise and the potential to be economically beneficial (either by reducing dependence on imports, bolstering a particular market, or providing new goods or functionalities), socially positive (including allowing local management of resources, job creation, or other societal gains) and environmentally benign (or the potential to be so) considering such aspects as GHG emissions, toxicity, resource depletion, habitat destruction, and water use.

As the list of candidate technologies was generated by the author research term, it was presented to experts in biotechnology, engineering biology, and science and technology policy (four workshops or seminars). The feedback received contributed iteratively to refinements of initial lists, with 18 technologies determined to best fulfil the requirements criteria and included on the short-list of promising biobased production technologies. (see Section 3 and Supporting Information S1: Supplementary Materials).

2.1.2 | Focus group (stakeholder engagement)

As part of the assessment approach, a focus group process was initiated to engage with stakeholders. Exemplary technologies were selected for further discussion and feedback in the focus group. The focus group facilitated a multi-discipline discussion about the feasibility, implications, and considerations associated with each exemplary technology, and identified associated roadblocks and considerations relating to its development and to its contribution and integration into the UK bioeconomy. The focus group (held online in January 2021) was attended by academic, scientific, governmental, regulatory, think-tank, policy, agricultural, and industrial stakeholders (10 attendees plus 2 research team members). Participants were asked to address three principal questions: (1) What are the specific challenges you see relevant to each of these specific technologies? For example, technology, management and/or regulation. (2) What are the main governance, funding and regulatory roadblocks you consider to be the most important and how can these be overcome? (3) Are there any other technologies you think should be included as exemplary case studies based

on the UK's native feedstocks, resources, expertise or policy context?

2.1.3 | Assessment case studies and target biobased technologies

Following feedback from the focus group, selected technologies were highlighted as presenting the most promising options for biobased production. The focus on these technologies was intended to allow for the development of in-depth case studies to pilot a targeted assessment method that could be made available for subsequent scale up to other biobased technologies. The case studies were undertaken using secondary data sources with a focus on the following probes: (1) Functionality: Technical specification, novel functions, and comparison to the status quo. (2) Sustainability: Source of feedstock, ability of UK to provide/import, and sustainability/environmental issues of production and consumption. (3) Development: Current use, and alternative and developing methods of utilisation, extraction, and valorisation. (4) Market and customers: Affected markets and customers, current and potential scale/growth/locations of the market, and potential market competitors. (5) Scaling: Potential for and requirements of scalability of the extraction/valorisation process, and examples of technologies in development. (6) Industry, investment and partnerships: Current industry structure, potential for redistributed (small-scale, decentralised) production, and capital requirements. (7) Governance: Regulatory aspects, public acceptance and possible opposition to this feedstock/technology. As part of each case, for each of the pilot target biobased technologies, consideration was given to multi-level policy options to foster responsible and sustainable development.

3 | RESULTS

3.1 | Long list to short list

As noted, a long list of 50 extant and emerging innovative bioeconomy technologies was identified through bibliometric and documentary analysis and expert workshop or seminar feedback. Review of these emerging and innovative biobased technologies yielded company-specific products, specific emerging technologies at varying development stages, and pathways to generate already biobased end-products. Technologies that did not fulfil the definition of biobased were removed, including solar, wind, and alternative energy-based technologies.

Of the initial 50 biobased technologies, 33 were progressed further. These technologies were assessed (drawing on expert input) for their ability to fulfil the five requirements for subset generation (see Section 2.1.1). Although some technologies are not presently environmentally benign, they were assessed on their capacity to be so with further development to balance the immediate need for these technologies with long-term potential. Eighteen technologies fulfilled the requirements criteria,

and from these six exemplary technologies were selected for further discussion (biomethane, high purity lignin, microfibrillated cellulose/nanocellulose, PHAs from fatty acids and urban waste, seaweed technology, and bioethanol) via a focus group. While not necessarily the most innovative of the technologies available, they were selected to represent a range of different feedstocks, low- and high-value products, and a diverse range of primary end uses, from energy, to biomaterials, to platform technologies.

3.2 | Focus group findings

In the focus group discussions, an early consensus was established that subsequent case studies should focus on specific native feedstocks, with feedstock-specific technologies considered within this overarching context, to address the conversation around management and utilisation to ensure sustainability. The downstream uses/technologies of each feedstock platform are extremely diverse, as are the environmental, social, and economic impacts. Consideration of environmental, social, and economic challenges, the potential for scale-up of a specific resource, and optimisation at the primary stage can influence products downstream but not vice versa. As such, a ground-up approach became the focus.

A core challenge envisaged for biobased feedstocks is that of supply chain, which needs to be sufficiently large to accommodate commercial demand whilst having a definitive economic and environmental impact. Due to the size of the UK and resource availability, it was recognised that it would be relevant to focus on small-scale, high-value opportunities. However, for there to be a large-scale effect on climate change, the UK would also need to export technologies where the balance is reversed (i.e. large-scale, low value). Utilisation of waste streams may be a way to negate this issue.

Activation barriers were identified as a potential roadblock. Extant systems with integrated supply chains, such as those reliant on fossil fuel feedstock, can function at a given economic scale. For these systems to transition to biobased feedstock, different supply chains may need to be established, potentially at a different scale, and requiring investment in alternative infrastructure, expertise and facilities. Such a transition would require both Government promotion, through initiatives and incentives for companies to develop and implement more sustainable biobased technologies, and markets and societal pressures to encourage companies to expedite this shift. A supportive and consistent government policy—addressing carbon pricing and carbon standards—would be needed to provide a framework that supports the transition to a low-carbon world.

3.3 | Case studies

Based on focus group feedback, assessment case studies were developed for cellulose, lignin, and seaweed to assess in greater detail the potential and scope of these feedstocks as the

foundation for development of a sustainable biobased UK. The case studies address the seven categories indicated in Section 2.1.3 (see also Supporting Information S1: Supplementary Materials).

3.3.1 | Functionality

Cellulose—the most abundant natural biopolymer with ~100 billion tons/annum available globally—is predominately derived from plant cell walls but is also present in many algae and oomycetes and is secreted by some bacteria. Cellulose is endowed with numerous attractive and exploitable properties—it is strong, insoluble in water and the majority of organic solvents, and biodegradable [41]. The usability and properties of cellulose depend on its degree of polymerisation, with long-chain and short-chains being preferable for different end-products.

Lignin, another plant-derived polymer, is the second most abundant natural polymer on Earth with ~20-billion tons/annum available globally [42]. Lignin has potential as a low-cost carbon precursor [43] as it comprises 30% of all non-fossil organic carbon, is CO₂ neutral, antimicrobial and biodegradable [44], and is the only known renewable source of extractable aromatic compounds from biomass [45]. Cellulose is commonly complexed with lignin, and hemicellulose as part of lignocellulosic biomass. Valorisation of this lignocellulosic biomass has numerous benefits; allowing the production of added-value chemicals, materials and fuels from a global renewable resource, thereby decreasing dependence on petroleum, and simultaneously improving the economics of existing lignocellulosic processes in the biofuel, and pulp and paper industries [46, 47].

Seaweed is of interest for applications in food, chemicals, cosmeceuticals, nutraceuticals, bioenergy and biofuels, due to an increased interest in ‘sea vegetables’, variety of cultivars, global bioresource availability, and the development of valorisation processes and higher-value biobased products [48]. While similar in many respects to terrestrial plants, there are differences in seaweed composition and development. For example, macroalgae have a higher concentration of many minerals and nutrients—including Ca, K, Mg, Na, Cu, Fe, I and Zn—compared to terrestrial plants in concentrations up to 10-times higher [49]. Seaweeds also typically have faster growth rates, higher productivity, and higher polysaccharide contents—similar in structure to that of land plants but different in abundance ratios.

3.3.2 | Sustainability

Extraction of lignin and cellulose is possible from first- and second-generation biomass, waste, and as a by-product of the pulp and paper industries and bioethanol production. The paper and pulp industry is the main producer of commercial grade lignin, with Kraft pulping alone producing ~130–140 million tons of lignin per annum [50, 51, 52]. However,

most of this is burnt to produce on-site heat/energy; only ~2% is used for higher-value applications [53, 54]. Recycled paper is another viable source of lignocellulose; 5.5 million tonnes of paper and cardboard were used in the UK of which 65.6% was recycled [55]. Paper fibres undergo recycling a limited number of times before fibre quality is compromised, so annual additional waste-paper residues amount to ~1.16 million tonnes [56]. The UK also exports ~4.2 million tons of paper for processing, which could instead be utilised [56]. Another source of cellulose is bacteria, which produce purer cellulose that has a higher water content, and higher tensile strength (due to a higher degree of polymerisation) [57] than plant-derived cellulose. This form of cellulose can be produced from numerous types of bacteria, usually via fermentation or reactor-based production, although this is not currently possible on an industrial scale.

Woodland is an important source of lignocellulosic biomass, but also for carbon sequestration, biodiversity, and as a natural system for flood and soil-loss prevention. Total UK woodland is estimated to be ~3.21 million hectares [58]. It has been determined that the proportion of woodland residues that can be removed without affecting soil stability and nutrient levels is around 50% [59]. Meanwhile, agricultural land accounts for around 62.8% of total land use in the UK [60]. First-generation crops and food-feedstocks are unsuitable for large scale production of bioproducts as: (1) they typically require good agricultural land and fertile soils, which is limited [61, 62], and (2) competition for use can contribute to food scarcity, and inflated food and animal feed prices [63]. Despite concerns about food security, the Waste Resource Action Programme estimates ~3.6 million tonnes of surplus food and food waste is generated annually on UK farms alone, equating to around 7.2% of total UK production, with an economic value of ~£1.2 billion. This could be used as a source of lignocellulose [64]. Interestingly, seaweed can help reduce emissions from agricultural, which is responsible for around 30% of all GHG emissions resulting from land use [65], by reducing dependence on environmentally damaging synthetic fertilisers [66], improving crop productivity and soil amelioration [66, 67], and through use as a prebiotic food additive to reduce methane emissions from cattle [66, 68], enhance livestock health [69, 70] and substitute antibiotics [71, 72].

The UK produces nearly 16 million tons of biomass waste per year, predominately in the form of municipal green waste (MGW). MGW is an abundant and consistent (both seasonally and spatially) source of lignocellulosic material (estimated content: 35%–50% cellulose, 31%–42% hemicellulose, 3%–35% lignin). Nearly 5 million tons/year of green waste are collected in the UK, accounting for 31% of the total waste biomass generated per annum [56]. Waste availability and sustainability depends on human consumption practices, availability of natural resources, and the diversion/processing of viable lignocellulose sources away from landfills [73], reducing the detrimental environmental, economic and social impacts associated with them [74–76].

Seaweed is not compounded by the same land use issues as lignin and cellulose. As a viable source of both food and third-

generation biomass, seaweed confers numerous environmental advantages, including acting as an anthropogenic CO₂ sink, regulating ocean pH and natural oxygenation and nutrient cycles, waste purification [77], bioremediation, and promotion of biodiversity [65, 78–81]. In addition, farmed seaweed is considered a carbon negative crop [65]. Problematically, the assessment of seaweed sustainability in the UK is compounded by a lack of information about the potential effects of scaling in European waters, invasion of non-native species, the risk of pathogens, losses to other industrial sectors (such as leisure and fishing), and competition with ecosystems that provide vital carbon sequestration services, such as seagrass meadows [82–85]. Proper evaluation and assessment of suitable locations for farms or harvesting in the UK is needed so potential conflicts can be mitigated and opportunities for development can be exploited. Data pertinent to productivity, yields, and optimal algal cultivars is needed to ascertain the scale of UK production that can be sustainably harvested.

3.3.3 | Development

Lignin, cellulose, and seaweed can all be considered bulk feedstocks. While they can be utilised as raw materials, it is through degradation to their component parts, and purification of these moieties, that they can be utilised for higher-value products. For example, for effective valorisation via fermentation or biotransformation, lignin must be broken down to mono- or oligomers to allow utilisation of its carbon. Different depolymerisation methods yield different/higher fractions of specific phenolic monomers, including vanillin, guaiacol, *p*-coumarate, benzoate and catechol, which are of particular relevance for downstream biochemical conversion processes. As such, the depolymerisation method needs to be optimised for the desired end-product, with preference given to methods that retain the integrity of other components to allow maximum yield of useable material from the original feedstock. The most effective pre-treatment methods for lignocellulosic material—physical and chemical—often produce unwanted by-products, causing environmental damage or inhibiting hydrolytic enzymes downstream. By contrast, biological pre-treatments are essentially environmentally impact free: exploiting enzymes or accessory proteins. Enzymatic extraction methods are in development, with numerous potential candidates for biochemical and synthetic biology approaches, including hydrolytic and glycosidic enzymes, cellulases, and cellulose-associated proteins [47, 86].

The UK has a long history of the harvesting of wild seaweed, but seaweed farming is not currently a well-developed industry. There is significant potential for the development of the seaweed sector given the UK's extensive coastline and expertise in macroalgal research, including algal taxonomy, cultivation, physiology, metabolism, biochemistry, and molecular biology [48]. However, the development of the UK seaweed sector is limited by numerous problems, including how to establish the industry at a large-scale sustainably, economic viability (especially considering the low cost of imports

from Asia), and development of high-value products. For example, expansion of seaweed aquaculture into offshore areas—allowing greater volumes to be cultivated—raises challenges in engineering technology able to withstand harsh environments and high salinity, as well as issues of decentralised energy supplies, reduced nutrient accessibility, and additional costs for transport and a skilled workforce. Aspects such as storage, pre-treatments, a viable supply chain, and the use of algal bioreactors for cultivation need to be developed further [48].

A particularly interesting area of development, which has no counterpart in the fossil fuel industry, is the use of synthetic biology and genetic modification to impart advantageous properties, or novel characteristics into these feedstocks. Future bioengineering approaches could, for example, impart genetic modifications that either reduce lignin content, allowing greater saccharification of biomass without compromising plant yield or growth, or modify the lignin structure to make it more amenable to chemical or enzymatic degradation under milder conditions [51, 87] by replacing recalcitrant ether bonds with more labile ester bonds. Synthetic biology approaches could be useful in the industrial application of these feedstocks, using native and engineered microbes to convert building blocks into bulk chemicals (typically through fermentation), and via biotransformation into smart biomaterials and high-value products [88]. For increased industrial application, breeding of efficient microbial cell factories needs to be expanded from the lab- and pilot-scale [89], and microbial strains need to be produced that allow operation at high levels [90, 91], have extended substrate specificities [52, 91–93], and allow integration of various production pathways.

3.3.4 | Market and customers

In 2019, the global lignin market size was estimated at US \$954.5 million with an expected compound annual growth rate (CAGR) of 2.0%, in the 2020–2027 period [88]. Demand for kraft-derived lignin (ligno-sulphonates) currently accounts for the largest market share of total lignin, accounting for 85.5% of demand in the US in 2019, with an expected CAGR of 1.6% between 2020 and 2027 [88]. The global cellulose market is significantly smaller, valued US\$219.53 billion in 2018 [94] and US\$211.68 billion in 2019 [95]. It is projected to rise to US \$305.08 billion by 2026 with a CAGR of between 2.9% and 4.2% while, the seaweed cultivation market had an estimated value of US\$16.7 billion in 2020, with a CAGR of 12.6% [96]. Global production of marine macroalgae, both wild-collected and cultivated, in 2018 was reported to be 32.4 million tonnes, of which 97.1% was from seaweed farms [97].

At present, markets for bioderived feedstocks can be broadly categorised into three groups: (1) direct use, (2) drop-in replacements for oil-based products, and (3) as a raw material for commodity or high-value chemicals, and value-added products. Lignin feedstock is predominately used for animal feed, and in the production of macromolecules used in biofuels and biorefinery catalysts [88] but, it can be used directly or for the production of a wide variety of chemicals and materials.

Products from delignification can be used directly (e.g. concrete/cement additives, glue, absorber and fertilisers; use depends on the delignification method), or can undergo pre-treatment and depolymerisation, via pyrolysis, cracking, solvolysis, acid/base catalysis, enzymatic or hydrogenolysis methods. Alternatively, these oligomers can go through aromatic funnelling to produce high value aromatics such as catechol and protocatechuic acid [93, 98]. Further processing is possible via biotransformation or fermentation, leading to direct use products for chemicals, fuels, materials and flavours.

Cellulose is a major constituent of both the paper and textile industries, but the development of novel cellulose-based products has expanded its market potential. Regenerated cellulose can be used for the manufacture of rayon, cellophane and viscose, textiles, medical devices, nitrocellulose, and artificial membranes. Microcrystalline cellulose is used in the consumables, food, and pharmaceutical markets as E-numbers, inactive fillers, and as emulsifiers, thickeners and stabilisers. Other potential uses of cellulose include as piezoelectric sensors, housing insulation and fireproofing, water-soluble adhesives and binders, filters and membranes, bulking agents for cement, as biodegradable matrices for the preparation of nanocomposites, and as reinforcing fillers for polymer-based nanostructured composites, thermoplastics and thermosets.

The lack of a diversified market for seaweed, and access to cheaper raw materials and labour from Asia, means there is significant competition and lack of opportunities/incentives for seaweed producers in Europe [48]. This could be helped by opening new markets, valorisation of seaweed to higher value and specialty products, and a substantial increase in seaweed production, which could be achieved by near-shore farming in the short-term, and further off-shore in the long-term as technology is developed to support this. It should also be noted that the monetary value of non-market public goods, such as ecosystem services, bioremediation, and biodiversity, are difficult to quantify and vary significantly dependent of seaweed site, species, and cultivation method [99]. More in-depth Techno-Economic Analysis of the seaweed industry can be found in the literature [100–102].

3.3.5 | Scaling

The upscaling and commercialisation of biobased technologies face several issues: availability of sufficient feedstock, the chemical recalcitrance and structural complexity of the feedstock, purity, the type and quality of the feedstock, and biocompatibility. This is true of lignin, cellulose, and seaweed. For sustainability and economic viability, upscaling needs to focus on biobased feedstock from extant side streams and waste, and development of cascading routes of production. Cascading routes can be used to prioritise production of high-value products, with waste and by-products of this process being valorised downstream to produce lower-value or bulk products. Using this approach, products can be removed and used at various stages of the production process depending on desired end-use or physical, chemical, and mechanical

properties. This cascading process requires optimisation of both upstream (e.g. delignification bioengineering, extraction) and downstream (e.g. depolymerisation, scale-up, cascading) processes [51] taking into account environmental, social and economic aims. Both 'high volume, low value' and 'low volume, high value' applications are needed for the full economic potential of these feedstocks to be realised [103, 104]. This allows maximum yield of marketable products for minimum feedstock.

Although pilot facilities for seaweed cultivation have been established in the UK, knowledge about the ecological impacts, yield, and operational costs are not sufficiently robust for real insight into the cost, both economically and environmentally, of scale-up and development. The lack of recent and accurate estimates of the size and composition of the UK's standing stock is a major problem for development and upscaling due to uncertainty about whether there are sufficient resources for industrial scale application. In 2013 UK seaweed production from wild harvest was estimated at approximately 2000–3000 dry tonnes [105]. However, this figure does not include the unknown quantities of storm-cast seaweed and subtidal kelp that are also collected. At present seaweed biomass represents only a small quantity (30×10^6 tonnes; fresh weight) of the total global biomass supply compared to terrestrial crops, grasses, and forests (16×10^{11} tonnes; fresh weight) [78]. Expansion and scale-up of seaweed aquaculture, especially into offshore areas, would require development of suitable technology and equipment, training of a skilled labour force, and new seaweed cultivators [65]. As scale-up of seaweed production may cause a decrease in market prices, discouraging farmers and investors, therefore, growth in seaweed cultivation needs to be coupled with the development of novel applications and high-value products [106].

3.3.6 | Industry, investment and partnerships

Seaweed aquaculture is currently limited in the UK and existing pilot farms—for example, Queen's University (Northern Ireland), SAMS and the University of Highlands and Islands (Scotland) and Swansea University (Wales)—mostly remain in the research and development stage. There are a number of UK algal projects (e.g. EnAlgae, At~Sea, BioMara, SeaGas, MacroFuel, MacroBioCrude) with aims to produce biobased products from algae, while Wave Crookes has become the first commercial UK sea farm. Around 80% of global commercial macroalgae is used for human consumption [107] but a wide range of products can be obtained from seaweed, both direct use, including human and animal feed, chemicals (e.g. hydrocolloids, phytocolloids, carrageenan, agar), fertilisers, bioactives for nutraceuticals and dietary supplements, cosmeceuticals, food ingredients (such as omega-3 fatty acids), natural food colourants and dyes, fertiliser, bioplastics, specialty chemicals (such as phycocolloids), and chemical feedstock, pharmaceuticals, probiotics [108], biofuel, and for bioremediation and purification services. Despite the opportunities for seaweed as a feedstock, it is not without its challenges, significant research

and investment needs to be made into the development and optimisation of the industry, including selection of preferential species for specific end uses, and for sustainability and economic considerations [109–111]. Aspects such as storage, pre-treatments, a viable supply chain, and the use of algal bioreactors for cultivation need to be investigated further [48].

Most commercial technical lignin is produced by Mead-Westvaco Cooperation and Borregaard Industries in the form of kraft pulp. While there are no significant, independent, UK companies creating technical lignin, the chemical industry is well established in the UK and integration of lignocellulosic feedstock into existing production streams is feasible. While the products of kraft pulping (mostly sulfonated) can be used directly as ‘low-value, high volume’ additives for concrete, glue, absorbers, emulsions, and fertilisers [112–115] the majority is burnt for energy generation rather than undergoing valorisation as they are unsuitable for many high-value applications [115, 116]. The need for technical lignin suitable for valorisation to higher value products (such as vanillin, phenol derivatives, phenolic resins, and BTX), and the notoriety of the Kraft process as environmentally damaging—it uses harsh chemicals, large quantities of water, and emits organosulphur compounds [117, 118]—could boost demand for Organosolv-derived lignin. The Organosolv method is both more environmentally benign and produces higher yields of high-purity lignin. Despite the efficacy of the Organosolv method, which results in a high degree of lignin removal (>70%) with minimal loss of cellulose (<2%) [51], industrial Organosolv pulping enterprises have mostly been limited to the pilot scale, with few lasting longer than 5 years. A notable exception is the Alcell process developed by Repap Enterprises Inc [51]. The inability of Organosolv to saturate the market, despite its competitive isolation ability and lower environmental toll, is thought to be due to two main factors: (1) establishment of Kraft mills are a multi-billion pound investment, meaning further investment and regulations would be needed to both fund and incentivise a change in the industry [51], and (2) a lack of high-value applications able to utilise the high-quality, sulphur-free lignin produced [119, 120].

Cellulose derivatives include, among others, commodity-use cellulose pulp, fibres, ethers, esters, microcrystalline cellulose and nanocellulose, and regenerated cellulose, which are used in the textiles, food, chemical, pharmaceutical, construction, paper, pulp, and materials industries [94]. There are a number of UK business established across these sectors, notably Cellucomp, FiberLean Technologies (Imerys and Omya), and Zelfa Technology. Cellulose for industrial use is mainly obtained from wood pulp (via the kraft process) and from cotton [57]. Cellulose derivatives hold three core advantages for the industry over their oil-based counterparts; cellulose as a feedstock is bio renewable, widely available from multiple sources, and comparatively low cost. However, there are disadvantages to cellulose and natural fibres that limit their industrial application: variable quality, limited maximum processing temperature, incompatibility with hydrophobic polymer matrices, aggregate formation, lower durability, and poor fire resistance.

3.3.7 | Governance

A shift to a biobased economy utilising lignocellulosic feedstock will inevitably increase demand on agriculture and woodlands, and it is important that this is done sustainably, which highlights the need for policy direction and incentives tied to soil carbon/soil microbiome/plant-soil interactions/soil additives to encourage a greater yield of biomass, carbon sequestration, and protection of biodiversity and limited resources. Human consumption practices need to become more sustainable and effective waste management strategies need to be implemented to ensure the availability of natural resources, and the diversion of viable waste feedstocks away from landfills [73], thereby reducing the detrimental environmental, economic and social impacts associated with them [74, 76].

Significant research and investment is needed to develop and optimise the seaweed industry. The absence of specific regulations for seaweed farming in the UK, which creates uncertainty for investors, alongside the lack of diverse and high value markets for end products, promotion and marketing, means there is insufficient interest from investors to supply the start-up capital needed. Investment is needed for scale-up, development of supply chains, downstream processing, innovation (e.g. strain development, algal bioreactors, seasonality), and infrastructure (e.g. storage, distribution). Economic incentives—such as those linked to climate change mitigation, and bioremediation—and additional funding for seaweed-based research is needed from the Government to incentivise investors and farmers, helping the seaweed industry overcome this hurdle.

4 | DISCUSSION

A core roadblock in the transition towards a bioeconomy is land use and whether there is sufficient biomass available to meet increasing demands. However, as we have discussed, land use issues can be addressed through the development of management practices that prioritise sustainability rather than intensification, and utilisation and integration of core feedstocks from a range of different sources. Rather than utilising biobased feedstock from first-generation biomass, which competes with crops for the food and feed industries, extraction and derivatisation of biomass from second-, third- and fourth-generation biomass should be prioritised. This includes, but is not limited to, waste (forestry, agricultural, industrial biomass-based and municipal solid organic), algae, fermentation of microorganisms, and through synthetic pathways. Waste-based feedstocks are a particularly promising source of lignocellulosic material as they are usually residues for which there is either no commercial demand, or the alternative to valorisation is disposal/low-value energy generation. Utilisation of waste streams as feedstock rather than higher value commodities can also confer social benefits when the development and management of feedstock is controlled in rural areas on a local scale rather than via nationwide or global management [18].

At present, we find that the cultivation, isolation, and utilisation of lignin, cellulose, and seaweed feedstocks in the UK is not entirely environmentally benign, although (unlike fossil fuels) they have the capacity to be so with further development and optimisation, and through the adoption of circular economy models, sustainable management, and technological advancement. Our approach here balances the need for immediate change, with long-term potential for development opportunities to further 'green' processes, improve economic competitiveness, and production of biobased products and technologies favourable or novel applications/functionalities. Development of these feedstocks presents a multi-faceted challenge. An obstacle to a biobased economy is the high associated costs, compared to fossil fuel-based alternatives. Although the costs of raw materials are relatively low, the production of biobased products tends to be dominated by subsequent processing costs, reducing their economic competitiveness with entrenched industries and products. By contrast, despite having high raw material costs and initial investment, the fossil fuel industry has low variable and production costs [15] due to sustained research and development over many years. While these variable costs may increase over time, as the finite fossil fuel resources are depleted, this is likely to be too late to avoid the environmental damage predicted for their continued use.

Despite broad scientific agreement on global environmental changes, and the need for global political consensus to engage with sustainable development, the political and regulatory frameworks required to implement the necessary changes have been compounded by a lack of impetus and direction, and entrenched supply chains resilient to change. For all three feedstocks presented here, there is a clear need for increased investment in R&D, more policy incentives to make the bioeconomy more competitive, and for a reduction in fossil fuel subsidies to level-the-field [121–124].

Research funding mechanisms that explicitly provide for collaboration between scientists and process engineers will help ensure that research is focussed on those areas most likely to significantly reduce processing costs. The main objectives are a close alignment of policy, science, and patents. Public-private partnerships and the creation of technological clusters are given high priority. While funding is strongly focussed on the life sciences, little attention is paid to other areas of research, such as agro-ecological farming, breeding of alternative crops for marginal sites, or social innovations [125]. For the three identified feedstocks, support is needed for the establishment and integration of biorefineries, which will allow optimal utilisation and valorisation of feedstock, by-products, and waste streams, thereby yielding maximum product from minimum feedstock.

Technological advances often come from academia but are unable to bridge the gap to become marketable innovations. More focus is needed in the UK to progress discovery science at early technology readiness levels (TRLs 1–2) to closer-to-market technology readiness levels (TRLs 7–9). De-risking of novel technologies is needed with more financial and operational support for start-ups and SMEs, for longer development

periods. Investment is also needed for scale-up, development of supply chains, downstream processing, innovation (e.g. strain development, algal bioreactors, seasonality), and infrastructure (e.g. storage, distribution). Even within the circular economy context, economic value is given precedence over other forms of value, such as environmental sustainability, amenity value, and ecosystem services [126–128]. Economic incentives linked to climate change mitigation, and bioremediation could encourage investors to overcome this hurdle [99].

The assessment of the three feedstocks and their potential input into bioproduction further surfaced needs for development of policy and legislation that supports the evolution of the bioeconomy in a sustainable way, prioritising environmental and social benefit. This requires a multifaceted approach that both bolsters biobased technologies, for example, through support for new markets for biobased technologies, and recognises benefit in excess of marketable goods, such as incentives linked to bioremediation and environmental services, and social and health impacts. Regulation that would, for example, allow crop modifications that produce more lignin, or make lignin more amenable to downstream processing, could be considered. Policy is also needed that levels the playing field with the fossil fuel industry, through initiatives such as carbon taxation, removal of oil subsidies, and legislation to make drop-in replacements more economically viable. A commitment is needed to long term systematic change, rather than short term fixes.

5 | CONCLUSION

We have presented a targeted assessment process where, for a single national economy (UK), we identified promising bio-based technologies from a larger set of bioeconomy technologies. From a longer list of potential technologies, we identified and evaluated promising possibilities using assessment criteria related to environmental, economic, and societal sustainability, and discussed them in a focus group. This led to the highlighting of three native feedstocks—cellulose, lignin, and seaweed—that could be utilised in the UK to advance biobased economic transition, with scope for differing functionalities and the potential for multifaceted applications. We undertook detailed analysis of these three target technologies, using a framework that examined dimensions of functionality, sustainability, development, market and customers, scaling, industry (including investment and partnerships), and governance. While each technology exhibited variations by these dimensions, we found overall that current capabilities were constrained. At the same time, we also identified pathways towards sustainable development and scale up through circular economy models, stakeholder engagement, and changes in policies and economic incentives.

In the UK, resource availability and type of feedstock depends on the regional landscape and this needs to be considered in the development of a bioeconomy. For example, while Scotland has the highest availability of woodland and forest residues, Southeast England produces the highest

fraction of MGW. Feedstock availability, and the academic, technological, and industrial expertise in each area of the UK needs to be assessed. From this, a roadmap for implementation of a suitable and bespoke biobased strategy for each area can be developed. Ideally, this should be associated with devolution so that local stakeholders input into the management of local and regional resources, allowing sustainable customisation to address local biobased production demands and opportunities.

Moreover, although Government has set out visions and targets, more specific attention to implementation and the operationalisation of biobased roadmaps is now critical. In particular, enhanced coordination and funding are needed to (1) support biobased production progression along circular value chains comprising feedstocks, biomanufacturing, marketable goods, and sustainable consumption (see, e.g. [129]); (2) foster innovation scale-up, support SMEs, and de-risk technological development investment; (3) strengthen roles for public and private intermediaries in supporting bioeconomy transitions [130]; and (4) enhancing capabilities for detailed techno-economic, sustainability, and societal assessments to guide decision-making and investment. There is a need for (5) better infrastructure for the accumulation and processing of waste for its use as feedstock and for (6) legislative and policy changes to generate frameworks and incentives for sustainable biobased transition and long-run support for systematic change.

Any new regulations, policies, or incentives need new types of conversation, deliberation, and governance where there is greater interaction and transparency between policy makers, government, industry and publics. The post-pandemic environment and heightened attention to climate change and global instability presents an unprecedented wake-up call to rectify previous failings. Committed policy, governance, and action steps along the lines identified in this paper would help to leverage a systemic shift to integration and implementation of a sustainable biobased economy.

We acknowledge limitations in this study. The targeted assessment approach, while informed by bibliometrics and analyses of available secondary data, depends on judgements made by the research team and selected experts and stakeholders about fit with key assessment criteria to select the most promising bioproduction technology approaches. The aim of the approach was not to exhaustively identify every possible technology, but rather to develop sufficiently diverse sets to inform discussion about the technologies in the context of broader economic, societal, and environmental sustainability and to highlight scaling challenges and policy issues. The use of a focus group to test and elaborate on these selections provides external review and input. In future work, the approach, with its focus on three streams of biobased production, could be scaled up and applied to a larger set of potential biobased technologies. However, going beyond a pilot study would require engaging a wider set of stakeholders to participate in assessments and multiple focus groups. Additionally, the study is focused on the UK. The findings do not necessarily apply to

other national systems, although the approach used could be adapted for use elsewhere.

AUTHOR CONTRIBUTIONS

Claire Holland: Conceptualization; data curation; formal analysis; investigation; methodology; validation; visualization; writing – original draft; writing review & editing. **Philip Shapira:** Conceptualization; funding acquisition; methodology; project administration; supervision; visualization; writing – review & editing.

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CONFLICT OF INTEREST STATEMENT

The authors have no conflicts of interest to disclose.

DATA AVAILABILITY STATEMENT

Additional data that supports the findings of this study are available in the Supporting Information S1: Supplementary Materials of this article.

PERMISSION TO REPRODUCE MATERIAL FROM OTHER SOURCES

None.

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SUPPORTING INFORMATION

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