Bioenergy Technologies for a Net Zero Transition

Outcomes of UK-India Bioenergy Research Scoping

Biotechnology and Biological Sciences Research Council
UK Research and Innovation India भारत
Engineering and Physical Sciences Research Council

Foreword

The report is part of scoping exercise led by UK Research and Innovation (UKRI)'s Engineering and Physical Sciences Research Council (EPSRC) and Biotechnology and Biological Sciences Research Council (BBSRC) and commissioned to Supergen Bioenergy Hub. The report is for UKRI, funded by UKRI India.

UKRI launched in April 2018. UKRI is a non-departmental public body sponsored by the Department for Business, Energy and Industrial Strategy (BEIS). Our organisation brings together the seven disciplinary research councils, Research England, which is responsible for supporting research and knowledge exchange at higher education institutions in England, and the UK's innovation agency, Innovate UK. Our nine councils work together in innovative ways to deliver an ambitious agenda, drawing on our great depth and breadth of expertise and the enormous diversity of our portfolio. http://www.ukri.org

UKRI India plays a key role in enhancing the research and innovation collaboration between the UK and India. Since 2008, the UK and Indian governments, and third parties, have together invested over £330 million in co-funded research and innovation programmes. This investment has brought about more than 258 individual projects. The projects were funded by over 15 funding agencies, bringing together more than 220 lead institutions from the UK and India. These research projects have generated more than £450 million in further funding, mainly from public bodies but also from non-profit organisations and commercial entities, attesting the relevance of these projects. www.ukri.org/india

This work was commissioned to inform UKRI/UKRI India priorities and pathways for innovation development in bioenergy with UK-India partnerships.

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The Supergen Bioenergy Hub works with academia, industry, government and societal stakeholders to develop sustainable bioenergy systems that support the UK's transition to an affordable, resilient, low-carbon energy future. The hub is funded jointly by the Engineering and Physical Sciences Research Council (EPSRC) and the Biotechnology and Biological Sciences Research Council (BBSRC) and is part of the wider Supergen Programme. Grant: EP/S000771/1

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Background

This research prospectus has been prepared in response to a request from UKRI/UKRI India. The Supergen Bioenergy Hub were commissioned to liaise with researchers in the UK and India to identify key areas where the two countries shared bioenergy research interests and collaboration could be mutually beneficial. In light of prevailing international travel restrictions all research reviews and engagement activity were carried out online. This was done via an inaugural online meeting to introduce the activity on 14 February 2022, discuss scope and agree priority themes for further investigation. These transpired to be:

1. Rice and other agricultural residues
2. Waste and circular economy
3. Algal biofuels and biochemicals
4. Anaerobic digestion
5. Fermentation
6. Gasification
7. Biorefinery and chemicals

Two “deep-dive” workshops where participants were able to identify in detail the key research challenges and issues for different research topics on 11 March 2022 and 17 March, 2022. Participants from academia, policy and industry sectors of both UK and India attended the workshop. The aim of the workshop was to identify research gaps and scope for future collaboration in bioenergy research, in line with the aspirations of COP26 and net zero transition.

Between these engagement events, work was carried out to review the status in each country and summarize key challenges and opportunities by a wide range of technical experts. In addition, updates were provided to funders of progress and key findings. This report represents our final synthesis of the various representations made by different researchers during the meeting. It includes some discussion of participants’ perceptions of opportunities for future work together and experience of effective research mechanisms and enablers. This report synthesizes the main information compiled for each of the 7 prioritized challenge areas above and adds reported experience and reflections by participants on effective collaboration mechanisms and methods within this subject and geographical context. Where possible we have given examples provided by participants of projects, activities or developments that exemplify wider discussion themes. These should not be interpreted as prioritization or endorsement of projects/examples; rather as specific examples that help enhance understanding of wider issues.

1. Biomass Feedstocks: Agricultural Residues and Organic Wastes (including rice straw and sugarcane bagasse)

The UK and India have very different land-use patterns, population demographics and agricultural interests/practices. While there is some forestry interest it is not dominant in either country. The UK has energy crop targets/ambitions, but these seemed less actively pursued in India. However, during our consultations researchers from both countries identified significant levels of agricultural residues and organic wastes as key biomass resources/feedstocks for sustainable bioenergy and bioproduct development. There was particular focus on ligno-cellulosic residues (including rice straw and bagasse in India; cereal straw and tree/plant residues in the U.K.) alongside the organic fraction of municipal and other waste arisings. So, while the origin of the feedstocks may be very different there are common interests in finding efficient conversion routes for ligno-cellulosic agricultural residues with sometimes challenging compositions and in finding added value conversion pathways for organic waste materials. A range of existing projects in both countries provide a firm knowledge base for such exploration, including those mentioned below.

1.1 Existing Research Landscape

The U.K. has significant experience of development and operation of energy conversion plant for cereal straws. Combustion has been most successful and widespread, but digestion, fermentation, gasification and hydrothermal liquefaction pathways have also been explored. Fundamental understanding of the feedstock properties and conversion challenges developed via various research projects (including early work by the Supergen Bioenergy consortium/hub) has allowed us to transfer the underpinning knowledge to other feedstocks, including rice straw and sugar cane bagasse, which are of greater interest in India. UK researchers have worked in conjunction with biomass rich countries, including e.g., a well-established rice straw to biogas project in the Philippines. Since 2011, Aston University (previously University of Manchester) and the University of the Philippines, Los Banos have been working with private companies to develop rice straw to biogas solutions. Funders have included EPSRC, DFID and Innovate UK, as the project has progressed through different development stages. A demonstration plant has been built and extensive work carried out on environmental assessment as well as socio-economic assessment of business models and opportunities with communities. This has incorporated interactions with Indian stakeholders. Further details can be found at Straw Innovations Ltd[1].

[1] https://strawinnovations.com/

Another example is the UK-India Rural Hybrid Energy Enterprise Systems (RHEES) project: a multi-Institutional research project started in 2013 as part of the Indo-UK BURD (Bridging Urban Rural Divide) programme. Supported by RCUK (UK) and DST (India) the major focus was to develop a hybrid renewable energy (biomass/solar) village in rural India with the provisioning of production of clean electricity, biogas cooking fuel and biofertilizer digestate. Development of rural business entrepreneurship was a key aim. Project partners from the Indian side included Tezpur University, IISc Bangalore and Jawaharlal Nehru University, and from the UK side are the University of Nottingham, and Loughborough University. Further details of the project can be found at:
https://www.nottingham.ac.uk/news/pressreleases/2011/april/burd.aspx

1.2 Research Gaps and Challenges

Previous work has shown significant national potential with gross agricultural crop residue potential in India: 686 million tonne per year; net agricultural crop residue potential in India: 234 million tonne per year (equivalent to 4.15 EJ or 17% of India's primary energy demand)[2]. interestingly this is actually a similar proportion of national energy demand as indicated by previous UK assessments[3]. In the UK much of this is cereal straw and animal manure; in India rice, wheat and sugarcane bagasse.

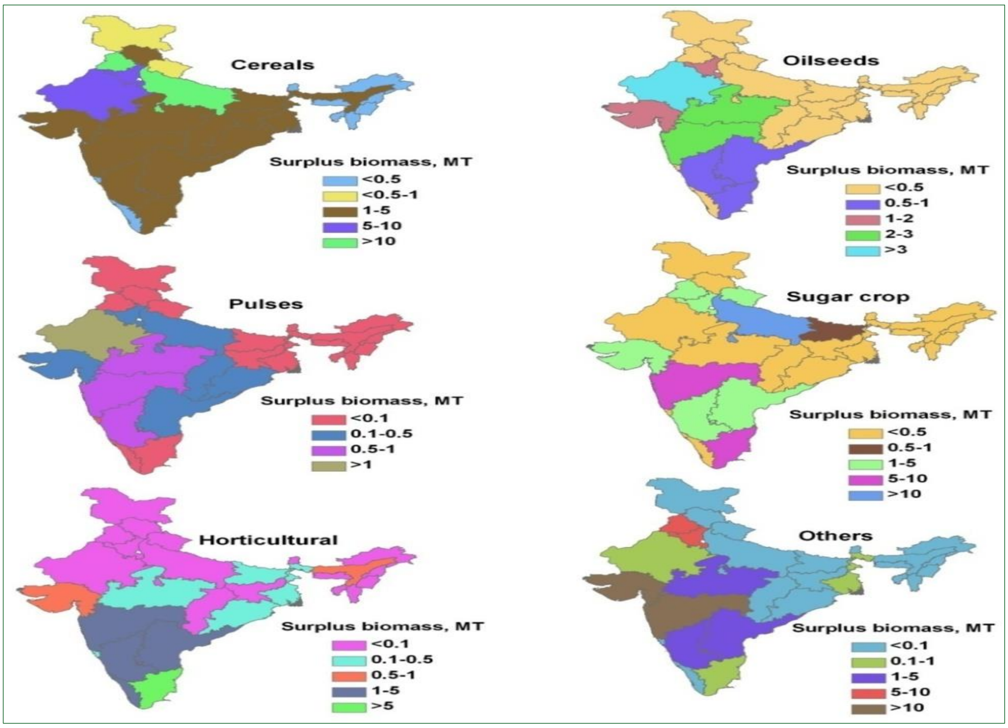

Figure 1. Spatial distribution of bioenergy feedstocks in India (Hiloidhari et al., 2014)

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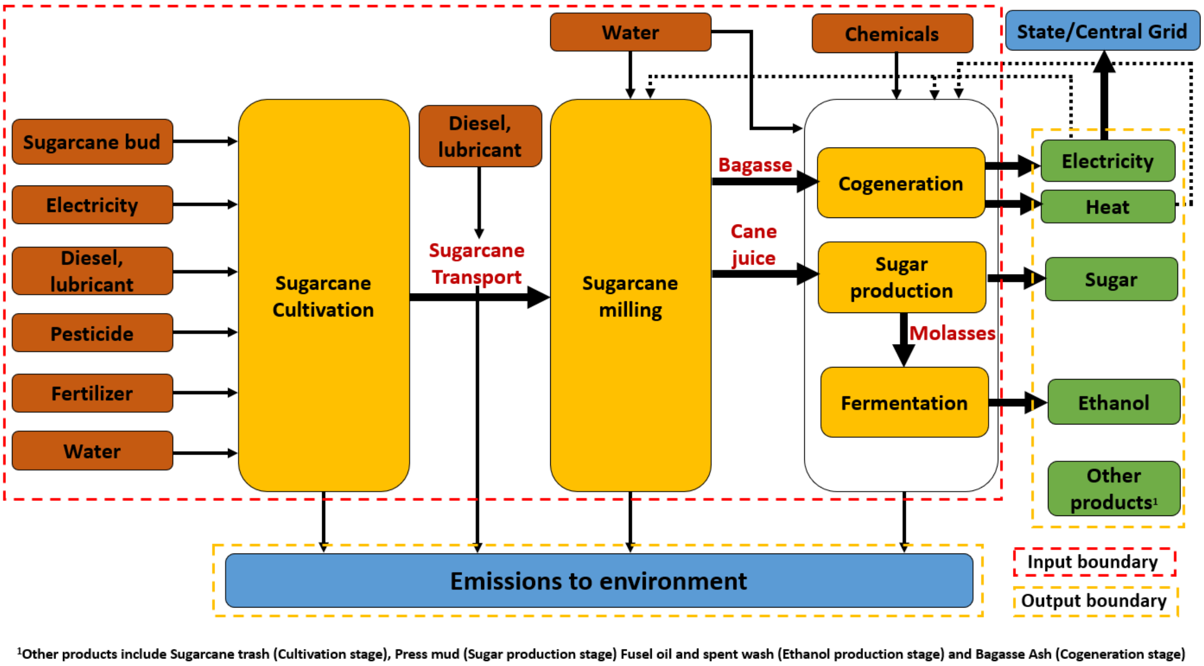
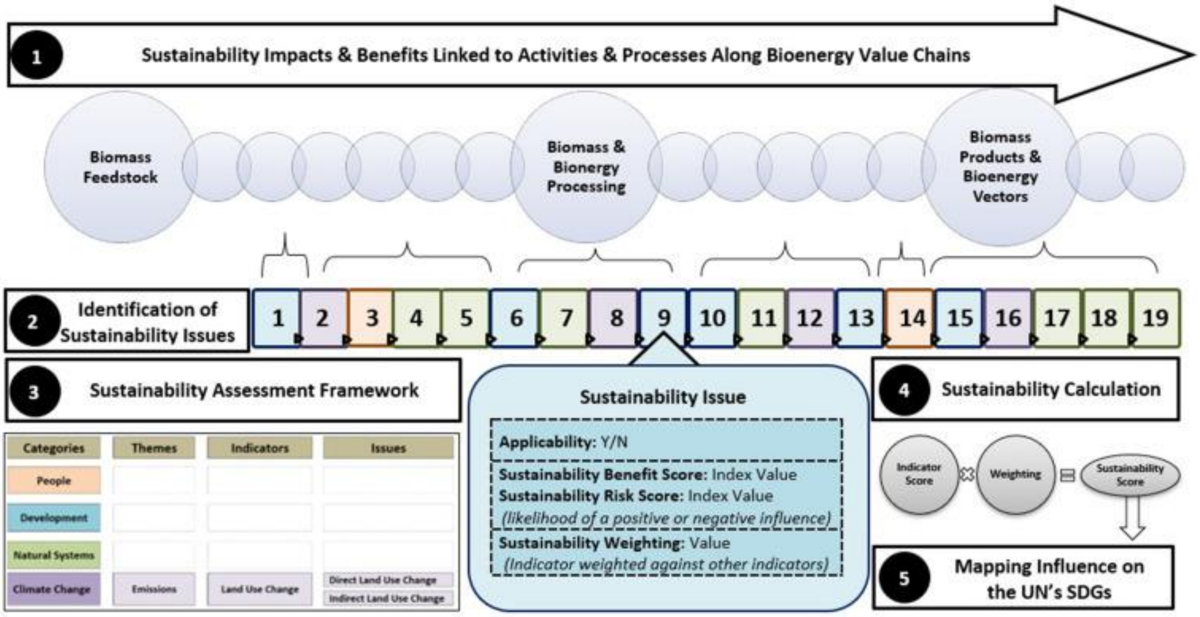
2 Hiloidhari, M., Das, D., Baruah, D.C., Bioenergy potential from crop residue biomass in India, Renewable and Sustainable Energy Reviews, 2014
3 Welfle, A., Gilbert, P., Thornley, P., Increasing biomass resource availability through supply chain analysis, Biomass and Bioenergy 2014

Detailed and up-to-date biomass resource inventory is critical for the long-term sustainability of bioenergy programmes in both countries and lack of biomass inventory at different spatial scales (village, development block and district) has been identified as a key research gap in India, while in the UK long term soil impacts of lower levels of residue incorporation are lacking long term experimental verification at scale. Both countries emphasized the importance of considering efficient biomass supply chains (considering all the elements such as plantation, harvest, collection, pre-processing, transport, storage, generation, and distribution) and a lack of private stakeholder investment. Another research gap identified is the nexus analysis of energy, carbon, and water footprints of bioenergy. Social and economic aspects of bioenergy are also important. It is emphasized that nexus analysis of bioenergy from life cycle assessment perspective is needed, with recent initiatives in both countries e.g., on sugar cane in India[1]:

Figure 2. Prevailing practices of agricultural crop residue biomass harvest, collection and transport in rural India (photo by Moonmoon Hiloidhari)



and across a wider set of agricultural residues in the U.K[4].:



1.3 Key Collaborative Opportunities

(i) **Biohydrogen, bio-CNG, and biojet fuel** are key policy foci of both the Government of the UK and India. However, there is limited information on the potential for agri-residue pathways to these vectors. R&D on biohydrogen and biojet fuel are still at laboratory/pilot scale level. Further research is needed on process optimization, feedstock selectivity/response and economic analysis are required.

(ii) R&D efforts to upgrade the **sugarcane industry** to biorefinery-focused operation could be a fruitful collaborative area to ethanol, electricity, non-fossil gas, biofertilizer and other **value-added biomaterials.**

(iii) Development of **biomass resource inventory tools** at different spatial scales using remote sensing, GIS and biomass supply chain design is another potential collaborative area.

(iv) **Life Cycle Assessment** of different biomass to bioenergy conversion routes (e.g., biohydrogen, bio-CNG, biojet fuel) to support development of sustainability assessment/frameworks would benefit from knowledge sharing between countries.

[4] Welfle, A. & Roeder, M., Mapping the sustainability of bioenergy to maximise benefits, mitigate risks and drive progress toward the Sustainable Development Goals, Renewable Energy, 2022

2. Waste and Circular Economy

Pledges to achieve net zero emissions over coming decades have compelled the Government of India to decrease its reliance on fossil fuels and look for sustainable energy through decarbonization. On the other hand, waste management has become a universal issue that matters to every single person in the world. It is estimated that about 500 million tons of agricultural and agro-industrial residues are being generated annually[5]. Adequate means of disposing of these wastes are lacking and a cascade of options for natural and anthropogenic waste is needed to convert them to value-added products moving towards circular economy concepts. Rapid infestation of invasive alien plant in various arable and non-arable settings is perceived to be a significant threat to biodiversity that could be turned to sustainable utilization towards a low carbon economy.

Both countries have significant experience and expertise in waste management and project deployment, with focus to date being mostly on energy production. Circular economy concepts to derive added value from waste and service much-needed sustainable material and product demands are gaining traction in both countries with significant interest, investigations, and initiatives, but limited commercial deployment. In the UK policy reviews have highlighted a need for more integrated and holistic support around scale-up but also the need for firm definition of sustainable/circular targets. [6] In India the following initiatives are particularly relevant.

Macro Initiatives influencing RE sector	
Initiative	**Targets**
Atma Nirbhar Bharat	• Under Make in India Manufacturing to become 25% of GDP by 2022. • Vocal for Local
Swachh Bharat Mission (Clean India)	• Open defecation free districts • Scientific waste management –SWM rules 2016 • GOBORDhan Scheme under SBM (R) • Oct 21- Mission focuses on **source segregation of solid waste**, utilizing the principles of 3Rs (**R**educe, **R**euse, **R**ecycle), scientific processing of all types of MSW • The outlay of SBM-U 2.0 is around **₹1.41 lakh crore**.
Smart Cities	• 100 smart cities by 2020 • Smart waste management system
Biofuel Policy (SATAAT) Sustainable Alternative Towards Affordable Transportation.	• Increased usage & promotion of biofuel • Assured offtake of CBG by OMCs
Paris Climate Deal (National Determined contribution)	• Renewable Energy to 175 GW by 2022 • Emissions reduction by 33-35 by 2030 (2005 base)

[5] Raji, S., Sarode, D.D. (2019). Study of Suitability of Biomass Wastes as Sustainable Fuel. In: Singh, H., Garg, P., Kaur, I. (eds) Proceedings of the 1st International Conference on Sustainable Waste Management through Design. ICSWMD 2018. Lecture Notes in Civil Engineering , vol 21. Springer, Cham. https://doi.org/10.1007/978-3-030-02707-0_64

[6] Energy Research Accelerator, Energy from Waste and the Circular Economy, 2020

	• Non fossil fuel mix in power to 40 % 2030
Oil import	• By 2022, reduction of oil imports by 10 % from 2014-15 levels
MNRE's Waste-to-Energy Programmes	• **Aug 21**-Financial Support scheme to **Promote Innovative organic waste to Energy biomethanation technologies** and Business model in India under GEF-MNRE-UNIDO PROJECT. • **May 21-** Programme on Energy from Urban, Industrial, Agricultural Wastes/Residues and Municipal Solid Waste" and "Scheme to Support Promotion of **Biomass-Based Cogeneration in Sugar Mills and Other Industries in The Country**"

2.1 Existing Research Landscape

Researchers in both countries flagged a significant number of projects including the following:

1. **EPSRC Project-** bridging urban rural divide biogas and gasification of waste, IIT Guwahati. Tezpur University and Indian Institute of Science, Bangalore.
2. **Newton-Bhabha Textile waste water treatment and energy production** with the help of Biological and Bioelectrical systems with Indore.
3. **Newton Fund Waste Valorisation** CMERI Durgapur Thermal and Biogas
4. **GCRF** "Valorisation of agri-waste with (parali) with IIT BHU, India
5. **GCRF Agrifood Africa Innovation Award** "Nutrient recovery from poultry Litter"
6. **SBM-Urban 2.0**/MNE WtE programme
7. **Newton-Bhabha Industrial waste Challenge**- Innovate UK, BBSRC, EPSRC, DBT India. Reducing industrial waste and pollution and improve value recovery from waste using biotechnology.
8. **Indian Institute of technology IIT, Guwahati (**Integration of PV/Solar/thermal/bio hybrid projects)
9. **Biofuel Lab at IIT Guwahati** (*Synthesis of alcoholic biofuels, bio pesticides, and biopolymer-value added products*)

2.2 Research Gaps and Challenges

The above projects and shared experiences have given multiple insights into barriers for different technologies, exemplified in the table below.

Research Bottleneck	Solutions Derived
Cost of feedstock, Biomass availability Supply and Logistics.	• Screened 8 multiple waste invasive plants based on holocellulose content and availability • Design composite feedstock based on sugar release time and kinetic constant.

	• 42.12 g per 100 g of raw biomass for composite biomass (8 biomass) • Kinetic constant of each available biomass can give desired sugar content based on a respective time
• Cost of Pre-treatment • Feedstock heterogeneity for increase biomass conversion	• Optimize a single constant pre-treatment method out of 17 different pre-treatment techniques for all biomass. • Establish a pre-treatment protocol to simultaneously utilized both sugar and Lignin.
• Cost of enzymes and processing • (Qureshi and Blaschek, 2000).	• Establish the physical mechanism of ultrasound induced enhancement of enzymatic hydrolysis • Secondary structure elucidation • Time profiles of reducing sugar release to the HCH-1 model for enzymatic cellulose hydrolysis. • Account adsorption, complexation, and inhibition of enzyme in free, adsorbed & complex form • 10-fold higher kinetics with time reduction from 120h to 10h.
• ABE Fermentation	• Sonication reduced fermentation period from 120 h to 92 h, and caused ~70% rise in ABE solvent yield • 0.288 g/g raw biomass in 92 h (9.10 ± 1.3 g/L Butanol), total ABE solvent 16.5 ± 2.6 g/L
• Ethanol Fermentation	• Total bioethanol yield from mixed feedstock of invasive weeds is ~ 220 g/kg. (87 and 133 g/kg) • 2-fold increase in kinetics. • Physiological status and heterogeneity within bacterial population was studied.
• Lignin Extraction	• 15% (w/w) pure lignin is obtained from the debarked bamboo waste. • The solubility of extracted lignin in various organic solvents (1-4 Dioxane, THF, DMF, etc.). • Highly pure, free from carbohydrate and mineral content and with low ash content (0.42 %). • Pyrolytic oil synthesized was rich in aromatic content (BTX) and high biochar content.
• Additional Research: Biopolymer (PHB Synthesis), Value added Product. (Xylitol and 1-3 Di propandiol. synthesis)	

However, these technology-specific issues sit within a wider framework where identified challenges include:

1. Lack of collaborative participation between Academia, Industry, and start-ups

2. Community based participation, Lake of awareness

3. Biomass inventory and efficient supply chain

4. Need for more private stakeholders through subsidies and Loan

5. Need for more pilot plant level study.

2.3 Future Collaborative Prospects

There are significant prospects for collaborative work around scale-up, commercialization, learning and innovation along commercialization pathways for different technologies. This can be split into project/concept-specific work, such as:

- Facilitation of scale up of Lignin extraction plants
- Scale up of bio product demonstrations including biopolymer (PHB) and xylitol production
- Analysis of residues/resources for fuel and product applications
- Investigation of nutrient recycling in crop and energy systems with a particular focus on fertilizer needs/nutrient balance
- Development of diagnostic tools e.g., for biogas plants
- Next generation biogas: Integrated approaches could be developed to compress methane into BioCNG, by removing CO_2 through bio scrubbing and further react to catalyst to produce green Hydrogen fuel.
- Household level biogas models could be explored.
- Black soldier fly larvae were flagged as a particularly promising area for further investigation. BSF larvae are voracious consumers of organic material with no risk of pathogenicity and Invasiveness. In current scenario, we have separate waste industry to convert preconsumer food waste to anaerobic digestion and aquaculture industry to convert fishmeal to protein feed. Black soldier fly farming can directly convert preconsumer food waste into high quality protein feed, while insect frass (manure) can be used as soil enhancer similar to compost. Future work could include development of smart larval farming technology, LCA of the whole process,

Other specific feedstock examples include invasive biomass, bagasse, and agricultural residues etc. as well as the need to consider climate-smart future crops. However, development of fundamental scientific knowledge that links this through to compositional traits will be most beneficial to a wide range of feedstocks. Positive experience of an IoT based integrated diagnostic tool for managing process parameters was also noted.

There is an acknowledged need for multiple technological pathways to be better supported in terms of moving beyond the laboratory to robust techno economic assessment and pilot plant evaluation. Both countries reported significant challenges in these areas, with arguably greater experience base in India. There seem to be significant mutual learning opportunities around sharing of these experiences and perhaps refining of the stages and support mechanisms for biotechnology commercialization/innovation support based on both country experiences. This includes private stakeholder Involvement in projects, where challenges around community or cooperative organization were reported and needs to strengthen wider understanding of bioenergy-specific aspects of renewable energy among stakeholders and researchers.

3. Algal Biofuels and Biochemicals

3.1 Existing Research Landscape

Algae (micro- and macro-) are attractive as biological chassis for the development of processes to produce biofuels and biochemicals, as they are photosynthetic and can be used to develop net-zero carbon emission processes[7]. Macro- and micro-algal production and research have been growing rapidly in the last few decades. Globally, over 97% of macroalgae (seaweed) is now cultivated rather than wild-harvested[8] and large-scale cultivation of microalgae in raceway ponds and photobioreactors for producing high value products has been widely practiced. However, the consensus for the use of algae for producing biofuels is that current strategies do not allow for favourable process economics to competitively produce a low value high volume product, such as biofuels. A biorefinery approach to source multiple products that enable favourable process economics is often advocated[9]. These processes require further scientific and engineering developments to improve productivities and maximise the production of compounds of interest, either directly or via bio/chemical/thermal conversions.

India enjoys a tropical climate, encouraging low-cost cultivation of microalgae in open ponds, but this affords little process control. Both India and the UK have vast coastal areas that can be developed for cultivation of macro and microalgae, primarily marine species, using seawater for cultivation. It is in the interest of both the UK and India to develop more controlled cultivation strategies that integrate with other sectors to optimally utilise resources available in the respective locations to cultivate algae for bioenergy generation.

There are separate funding opportunities within the UK and India for research on microalgae, macroalgae or both, for example the Network in Industrial Biotechnology and Bioenergy Algae-UK (2020-2024); and Department of Biotechnology (DBT) and Department of Science and Technology (DST) initiatives in India including support for the establishment of a national repository for microalgae and cyanobacteria (both marine and freshwater) in south India. However, the authors are only aware of one recent funding call which has run between the UK and India, run through the Biotechnology and Biological Sciences Research Council (BBSRC) in the UK and DBT in India. Sustainable bioenergy and biofuels (SuBB) ran 2013-2017 and funded

[7] Adams, J. M. M., Morris, S. M., Steege, L., Robinson, J. & Bavington, C. 2021. Food-Grade Biorefinery Processing of Macroalgae at Scale: Considerations, Observations and Recommendations. *Journal of Marine Science and Engineering,* 9**,** 1082

[8] FAO 2020. Yearbook. Fishery and Aquaculture Statistics 2018. Rome: FAO.

[9] Fernand, F., et al. (2017). Offshore macroalgae biomass for bioenergy production: Environmental aspects, technological achievements and challenges. *Renewable & Sustainable Energy Reviews* 75: 35-45. Thomassen, G., M. Van Dael, et al. (2019). "A multi-objective optimization-extended techno-economic assessment: exploring the optimal microalgal-based value chain." Green Chemistry 21(21): 5945-5959. Butler T, Kapoore RV & Vaidyanathan S (2020) *Phaeodactylum tricornutum* : a diatom cell factory. *Trends in Biotechnology*, 38, 6, 606-622 (DOI: 10.1016/j.tibtech.2019.12.023).

four UK-India programmes, two on microalgae, one on macroalgae biofuels, and a fourth on rice husk to biofuels[10].
Several other initiatives, including Newton-Bhabha projects have included PhD and post-doctoral exchanges, as well as visits from partners in both locations during kick-off and annual project meetings for the SuBB funded initiative.
Algal processing is continuously developing and with the current international energy instability caused by COVID-19 and the ongoing Russian conflict with concomitant disruptions to the supply of natural gas, the need to utilise third generation biomass in all its forms for bioenergy and bioproducts has increased. Processes can be developed that minimally utilise natural resources and instead rely more on waste generated from other industries/sectors/communities to maximise algal productions. Macroalgae can be grown without requiring freshwater, fertiliser or land[7]. Microalgae can photosynthesise more efficiently than terrestrial plants and have been shown to grow well in waste streams[12], efficiently locking CO_2 away or processing it for conversion to valuable products and energy generation in biorefineries[11] Microalgae can be grown in controlled cultivations in proximity of locations with available resources, as feedstock for energy generation with more defined characteristics for a non-disrupted supply chain, unlike waste resources, which can be affected by supply chain dynamics.

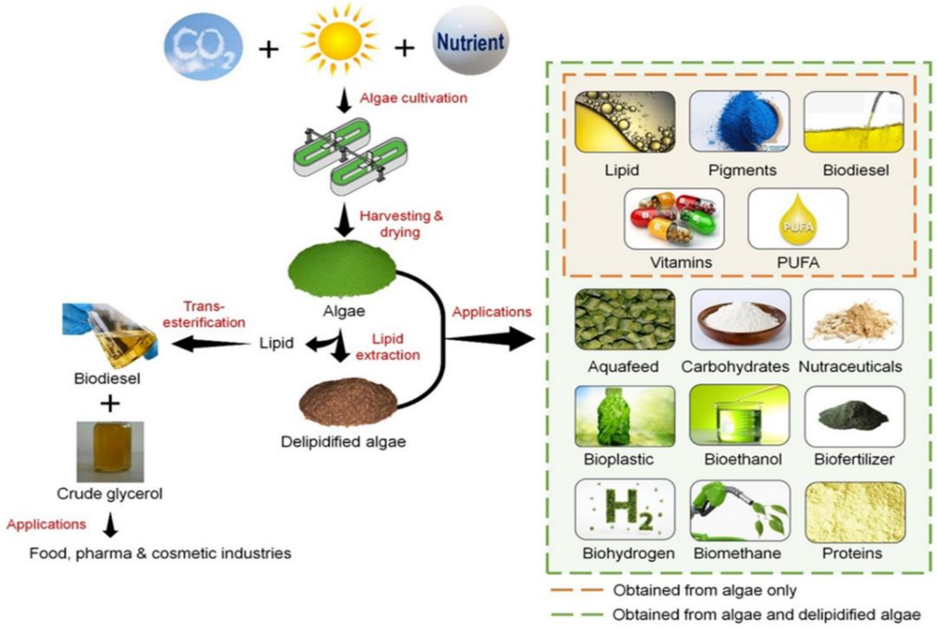


Figure 1[12]

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[10] (https://www.nanowerk.com/news2/green/newsid=33219.php).

[11] Butler T, Kapoore RV & Vaidyanathan S (2020) *Phaeodactylum tricornutum*: a diatom cell factory. *Trends in Biotechnology*, 38, 6, 606-622 (DOI: 10.1016/j.tibtech.2019.12.023). Sethi D, Butler TO, Shuhaili F & Vaidyanathan S (2020) Diatoms for carbon sequestration and bio-based manufacturing. *Biology*, 9(8), 217 (DOI: 10.3390/biology9080217)

[12] Shyamali Sarma, Shaishav Sharma, Darshan Rudakiya, Jinal Upadhyay, Vinod Rathod, Aesha Patel & Madhuri Narra (2021). Valorization of microalgae biomass into bioproducts promoting circular bioeconomy: a holistic approach of bioremediation and biorefinery. 3 Biotech, 11, 378.

3.2 Research Gaps and Challenges

Six key **gaps in the algae fields** within the UK and India currently require further investigation. These are as follows:

1. Enhanced CO_2 and effluent utilisation with improved productivities. Using CO_2-rich industrial streams to improve growth rates whilst lowering industrial impact on the environment (predominantly microalgae). This should use a circular economy-focussed approach, collaborating with industry or research with an industrial focus to use waste gas and liquid streams for algal production[13]. The need is to develop leads relevant to specific type of industries, where the requirements differ. The goal should be to enhance the productivities of desired energy vectors and/or algal biomass if the objective is to convert the algal biomass to biofuels or energy, with concomitant net-CO2 reduction gains. Current productivities do not allow for an economic translation of available technology.

2. Synthetic biology and traditional breeding. Synthetic biology approaches are emerging as a tool to develop innovative strategies not available in nature. It is well known that the algal world is quite diverse in habitat, response to environmental challenges and in metabolic versatility, yet only a handful of algae have been examined to any depth. Strategies to select for algal types with desired characteristics to maximise bioenergy production are needed, in addition to efforts to understand and effectively utilise algal photosynthetic capacity. Development of implementable metabolic engineering strategies of algae to improve pathway efficiencies (including CO_2 fixation pathways), to generate biomass with the appropriate characteristics for products of interest including for energy generation and/or high productivity rates are needed.

3. Initial handling and pre-treatment. Biomass storage and pretreatment strategies are required to prevent tissue degradation and loss of quality in high moisture-content algal feedstocks. These should be innovative and take energy efficient approaches to harvesting biomass, maintaining quality and initial processing steps. They should also minimise downstream processing requirements, including the cost-effective extraction of relevant energy components where needed.

4. Product diversification. Microalgae is more than biodiesel; blooming macroalgae more than a beach nuisance to be pushed offshore or put into landfill. There is great scope to examine the development of other energy vectors including short-chain fatty acids, alcohols, biomethane and biohydrogen, using algal biomass as feedstock. Other products for consideration should include jet fuels, hydrocarbons,

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[13] Wang, Y., Ho, S.H., Cheng, G.L., Guo, W.Q., Nagarajan, D., Ren, N.!., Lee, D.J. & Chang, J.S., 2016 Perspectives on the feasibility of using microalgae for industrial wastewater treatment. *Bioresour Technol,* 222**,** 485-497.

bio-oil, polymers, bioplastics and fibres generated through net-zero or net-carbon negative processes.

5.Biorefining. Co-production of high value products in addition to bioenergy is needed to help address process economics. By identifying specific industries in India and the UK we can establish algal biorefineries to convert process residues and effluents into valuable products, crucially including one or more high value products as well as energy generation

6. Process enablers and analysis. We need streamlined, simplified systems for setting up macroalgal and microalgal facilities including licensing; handling biomass and data generated; and assessing the processing and products generated for economic and environmental viability through LCA / TEA. Machine learning/ computational approaches and process modelling could also be applied more here.

3.3 Future Collaborative Opportunities

All the six areas identified as gaps are suitable for collaboration between the UK and India. An overarching requirement is to consider the circular economy, including potentially aligning with industrial residue processing, to minimise or remove negative environmental impacts. Relatedly, processes have to be sustainable, with minimal demands on water, nitrogen, phosphorus, and other resources. A further point is that the focus should be on cultivation rather than wild-harvest algae. Using cultivated algae provides homogeneity of feedstock such as species, age, composition; as well as preventing harmful over-harvesting and negative impacts on the environment and bio-diversity.

3.4 Institutes and Companies in India and the UK Working on Algal Research, Producing or Processing Algae

Indian Institutes* with recent and continuing algae research activities:

Indian institute	Area of research/ products
CSIR- CSMCRI	Marine algae research station, macroalgae
DBT ICGEB Advanced Bioenergy Research	Algal Omics, Biofuels, Bio based chemicals
DBT-ICT Centre for Energy Biosciences	Value added products from microalgae, genetic engineering of algae for drop in fuels and high value products
DBT PAN IIT Centre for Bioenergy	Bioenergy from algae
DBT TERI Centre of Excellence	Advanced biofuels and biocommodities
Institute of Chemical Technology-Engineers India Limited	Large scale cultivation, value added products
National Fisheries Development Board	Seaweed cultivation
NIIST, Trivendrum	Harvesting of microalgae
NIT, Tiruchirapalli	Biodiesel
Sardar Patel Renewable Energy Research Institute	Biofuels, Industrial effluent remediation, value added products

UK Institutes* with recent and continuing algae research activities:

Aberystwyth University	University College London
Aston University	University of Edinburgh
Bangor University	University of Exeter
Heriot-Watt University	University of Glasgow
Imperial College, London	University of Greenwich
Newcastle University	University of Leeds
Plymouth Marine Laboratory	University of Liverpool
Queens University, Belfast	University of Manchester
Scottish Association of Marine Sciences	University of Sheffield
Swansea University	University of Southampton
University of Cambridge	University of York

Indian companies* working on algae:

Indian company /startup	Area of research/ products
Green Bubble Algalworks Pvt. Ltd.	Nutrition derivatives viz. vitamins, minerals, antioxidants, omega oil supplements
Hindustan Petroleum Corporation Ltd.	Biofuels from algae
Indian Oil Corporation	Biofuels from algae
Phycospectrum	Bioremediation, Spirulina for nutrition
Reliance Industries	Carbon dioxide sequestration, HTL of algae for biofuels
Sea6 Energy	Seaweed cultivation
Zaara Biotech	Algae as alternative food source

UK companies* working to cultivate or process algae:

UK company	Predominant area
Car y Mor	Macroalgae – food
Cornish seaweed company	Macroalgae – food, cosmetics
Hebridean seaweed	Macroalgae – animal food
Mara seaweed	Macroalgae – food
Marine Biopolymers	Macroalgae – extracts
Oceanium ltd	Macroalgae – packaging, bioplastics
Notpla	Macroalgae – packaging
Pembrokeshire beach food company	Macroalgae – food
Seagrown	Macroalgae – cosmetics, textiles, chemicals
Selwyn’s seaweed snacks	Macroalgae – food
Algaceuticals	Microalgae – oils and chemicals
Algaecytes	Microalgae – nutraceutical, personal care
Algenuity	Microalgae – dyes
Axitan	Microalgae – animal feed
Glycomar	Microalgae - healthcare, personal care
Industrial Phycology	Microalgae – waste water treatment

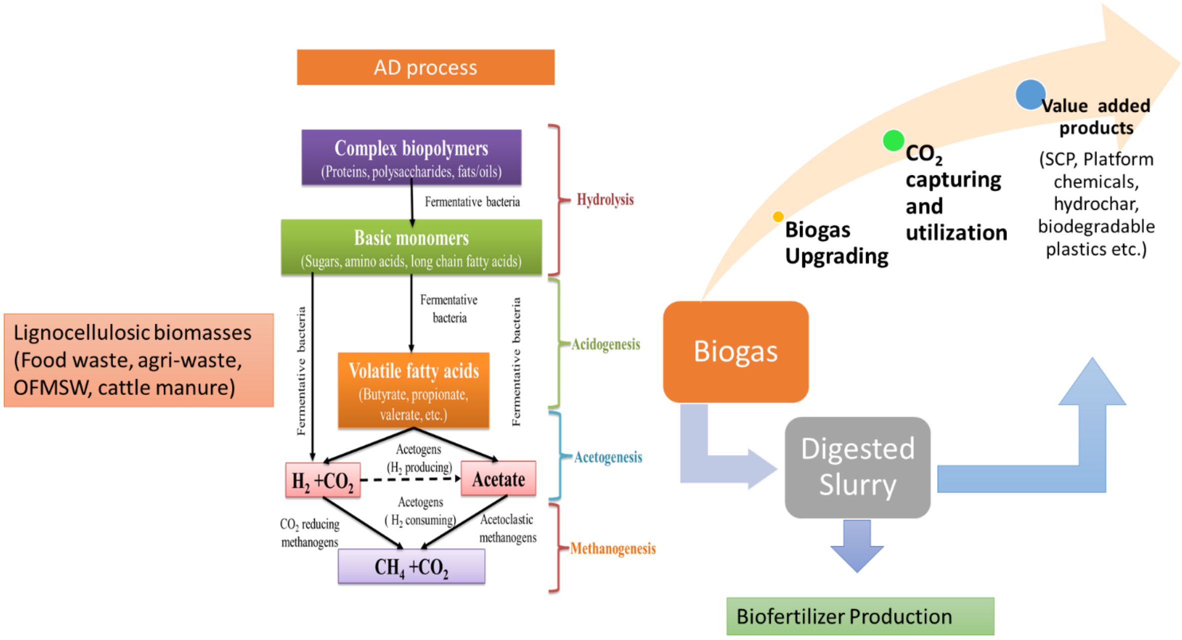
Kilbride Biotech Group Ltd	Microalgae- flue gas cleanup
Living Ink	Microalgae – dyes
MiAlgae	Microalgae – omega-3 production
Neptunus Biotech Ltd	Microalgae – cosmetics, animal feed
Nost.Algae	Microalgae - dyes
Phycobloom	Microalgae – oil for transport fuels
Phycofeeds	Microalgae – animal feed and fertiliser
Protein Technologies Ltd	Microalgae – specific protein expression
ScotBio	Microalgae – food, cosmetics, textiles
Greenskill Ltd	Both - photobioreactors
Membranology Ltd	Both – membrane filtration
Perlemax	Both – bubble tech for growth
uFraction8	Both – membrane filtration
Teegene Biotech	Both - Biosurfactant company
Varicon Aqua	Both - photobioreactors
Xanthella Ltd	Both - photobioreactors

* non-exhaustive list

4. Anaerobic Digestion (AD)

Anaerobic Digestion (AD) is a process in which microorganisms convert organic waste (any organic non-woody material) into biogas and digestate in the absence of oxygen, as shown in figure 1.

Figure 1. An overview of AD process and possible research interests.



AD provides a locally based, environmentally friendly waste management solution that helps us remove waste from landfills, reduce greenhouse gas emissions, and generate renewable energy. AD has the potential to benefit a variety of groups in society, including farmers and entrepreneurs, the food processing industry, local communities, the environment, and government[14].

4.1. Existing Research Landscape

United Kingdom

In the United Kingdom, there are now 650 active AD facilities (excluding typical water treatment plants). [15]The digester can be wet or dry, mesophilic, or thermophilic, single, or multistage, although the mesophilic, wet, single design is the most popular in the UK. Food waste from both residential and industrial sources, as well as farm manures and slurries, sewage sludge, and purpose-grown crops, are used as feedstock. In 2019/2020, 34% of the feedstocks used in operational plants were derived from crops (4.7 MT). The vast majority of this (4.2 MT, or 30% of total feedstocks) was crops grown specifically for AD, with crop waste accounting for 525 KT (3.8% of total). Non-crop wastes accounted for the remaining 66% of feedstock

[14] Bioresource Technology, 2009, 100, (22), 5478-5484.
[15] https://www.biogas-info.co.uk/

tonnage[16]. There are several ongoing projects in the UK, including the $32.8 million Selby Renewable Energy Park project, which will power nearly 11,000 homes while diverting 165,000 tonnes of food waste from landfills each year, as well as the project that received wrap support from the Environmental Transformation Fund (ETF) and case studies of agricultural and horticultural facilities. So far, the major contribution from AD is in the production of electricity. In particular, AD-produced electricity contributed the most to total energy production in 2020, accounting for 953 thousand tonnes of oil equivalent, a marginal increase over 2019. (947 thousand tonnes). Heat produced by AD accounts for approximately 6.7 percent of total heat energy contribution in 2020 (68 thousand tonnes of oil equivalent), the same proportion as in 2019.

India

In India AD technology has potential to convert various organic wastes like agricultural, animal, industrial and municipal into biogas with the ease of reduced reliance on fossil fuels while also boosting rural energy access in India[17]. As of now, most of the biogas digesters are based on mesophilic AD technology and with approved digester designs by the Indian government: namely fixed dome, floating drum, bag type fabricated and prefabricated models. The major feedstocks used for AD processes include agricultural waste, cattle dung, piggery waste, sewage sludge, organic fraction of municipal solid waste, animal manure, industrial waste (sugar mills, dairy, paper, and textile etc.)[18]. To date, more than 5.05 million small scale biogas plants, about 300 medium scale biogas plants, more than 190 large scale plants for power generation and 90 CBG generation plants have been installed. Currently, the total biogas production in India is 2.07 billion m^3/year. This is quite low compared to its potential, which is estimated to be in the range of ~ 48 billion m^3/year. For the past three decades, India has promoted biogas technology through a variety of government-sponsored initiatives like MNRE with the goal of producing 10 GW of electricity generation from bioenergy and 100,000 small-scale AD plants by 2022 and SATAT scheme under MoPNG to install 5000 CBG plants to generate 15 MMT/year biogas with 50 MMT/year bio-manure by 2024[19]. India has a large installed gas power capacity, but this is underutilised because of lower-than expected domestic natural gas production, which dropped from ~120 MWh in 2009 to ~50 MWh (2018), leaving several power plants stranded, unable to afford higher-priced imported gas.

4.2 Research Gaps and Challenges

To promote commercial AD, the major challenges are data management, regional expertise, waste management, collaboration between stakeholders, and supply chains. Agri waste has enormous potential for AD in both the UK and India, but it has yet to be fully explored due to several challenges encountered during the

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[16] Anaerobic digestion deployment in the UK- https://www.nnfcc.co.uk/publications/report-anaerobic-digestion-deployment-in-the-uk
[17] Bioresource Technology Reports 16 (2021): 100830
[18] Energy Policy 112 (2018): 361-370
[19] Bioresource Technology Reports 16 (2021): 100830

implementation of agricultural-based AD processes from pilot projects to industry projects. The key challenges are the appropriate temperature, optimal pH, C/N ratios, and proper biodegradability of lignocellulosic biomasses with digestate utilization[20].

Many large-scale commercial biogas plants have recently been commissioned for BioCNG production. All of the plants are in working mode but dealing with the massive volume of slurry that is produced is a major challenge. Also, because the digested slurry generates very little revenue, it attracts fewer entrepreneurs and farmers. The slurry is primarily used as organic fertiliser, but there is a need for additional research activities to develop new value-added products in order to increase farmer income.

As next generation ADs, co-digestion with best AD practises could be a viable option. Pre-treatment, temperature, pH, organic loading rate, impact of additional feedstock (animal manure, food waste, or microalgae), and C:N ratio are the most important factors to consider in development of co-digestion-based AD[21].

Small scale (family-based) ADs, on the other hand, have been widely promoted and supported in India, but they are associated with significant financial and economic barriers, such as high transaction and installation costs, as well as social and cultural barriers that impede rural biogas technology adoption. Here the medium-scale (community-based) and large-scale ADs provide more financial and economic benefits, but they require effective collaboration between the government, experts, socialists, and community leaders to break down social and cultural barriers. For example, rural India requires a strategy to raise awareness in rural communities about the use of AD technology to increase land productivity, thereby increasing farmers' net income and reducing crop residue burning[22]. Furthermore, because no AD technology can be used for all situations or feedstocks, the most appropriate technology based on regional feedstock potential with best AD practises is essential. This would aid in gaining the trust of the local community, as well as breaking down social and cultural barriers through education on potential societal and economic benefits[23].

Other research challenges and gaps raised by participants included:

- Storage challenge for biogas/bio-CNG
- Affordable CO_2 capturing and utilisation
- The lack of deployment of this bioorganic fertilizer as opposed to inorganic fertilizer is a hurdle to public acceptance of this technology.
- Development of equipment (technology support in India) for the handling of digestate for commercial plants

[20] Bioresource Technology Reports 16 (2021): 100830
[21] Journal of environmental management 236 (2019): 396-412
[22] Biomass Conversion and Biorefinery (2020): 1-12
[23] Energy Policy 112 (2018): 361-370

- Production of value-added products like microbial protein (SCP), platform chemicals, hydrogen, aviation fuels, biodegradable plastics, hydrochar, methanol etc., along with biogas.

4.3 Collaborative Research Potential

One way or progressing AD exploitation would be development of regional circular centres. If a supply chain to provide enough organic wastes (of all suitable feedstocks) is established in both the UK and India, the co-digestion process can be used as a core technology to supply biogas and biofertilizer. Furthermore, India and the United Kingdom could collaborate to develop optimization strategies, such as substrate pre-treatment and system configuration and control; maximizing the economic benefits of digestate utilisation through nutrient recovery and use as a biofertilizer. This could also provide a platform to work together on new value-added products such as single-cell proteins, hydrochar, platform chemicals, bioplastics, and others, which will increase revenue while also being environmentally beneficial. This is a much-needed shared interest for both India and the United Kingdom.

Removing a high amount of CO_2 from biogas is a critical step in the biogas value chain, and solvent selection is one of the most important steps. Conventional solvents, such as amines, meet the target recovery and purity of biomethane, but high energy consumption and environmental concerns are significant challenges that must be overcome. Therefore, another area of opportunity for India UK is biogas upgrading using appropriate green solvent blends.

The majority of biogas equipment in India is imported from Germany and the United Kingdom. The cost is very high in terms of the Indian economy because it is imported from the developed countries. The technology support and manufacturing of technology in India will drastically lower the overall cost of biogas production on a commercial scale, ensuring the system's technoeconomic viability.

Much of the recent significant increase in the amount of energy produced by AD in the UK can be attributed to a number of support mechanisms designed to provide financial incentives to bridge the cost gap between conventional and renewable energy sources such as AD, as well as expertise and technical support for new start-ups. The non-domestic Renewable Heat Incentive, for example, provides payments to encourage the production of renewable heat. This has partly been supported by the existence of organisations, such as the NNFCC, that have been able to provide access to data and expertise for small businesses and technology developers. So, there may be scope to look at how each country can learn from the knowledge transfer mechanisms that have been effective in both countries, as well as comparative examination of policy and support frameworks.

5. Fermentation

Fermentation technology can play a significant role in achieving a robust circular economy and net zero emissions. Scalable and cost-effective fermentation processes resulting in valuable biofuels and biochemicals from sustainable waste resources are of considerable interest. The two traditional biofuels produced by fermentation are ethanol and butanol. In first generation systems these are produced from sucrose-based crops such as sugar beet and sugar cane or starch-based crops such as wheat, barley, rice etc. To address the fuel vs food debate, considerable research has been directed at producing fuels from wastes or from cellulosic materials such as rice or wheat straws to reduce the competition with food resources. This goal has furthered to develop fermentation which can utilise gases such as hydrogen, carbon monoxide and carbon dioxide produced from non-fossil fuel routes such as renewable energy powered electrolysis, gasification of organic wastes or from industrial waste gases i.e., from steel works, but significant gaps and challenges remain.

5.1 Existing Research Landscape

India

Biofuel policy 2018 of the Government of India aims to achieve by 2030 a target of 20% blending of ethanol in petrol (current is ~2%) and 5% blending of biodiesel in diesel (current is <0.1%). This will be achieved by multi-pronged approaches leading to domestic production of bioethanol, biodiesel, advanced biofuels, drop-in fuels, bio-CNG, bio-jet fuel, bio-methanol and DME from sustainable multiple non-food feedstocks. At least 12 ministries (such as Ministry of New and renewable energy, Ministry of petroleum and Natural gas, Ministry of environment, forest and climate change and few others) have defined roles towards achieving the vision. The funding bodies such as DBT, DST and others are facilitating national and international cooperation via technology projects in Bioenergy (e.g. Indo-UK Newton Industrial Waste Challenge; DBT PAN-IIT centre for Bioenergy). A recent PM (JI-VAN) Yojana scheme in 2019 is supporting at least 12 commercial scale units that would integrate Bioethanol Projects using Lignocellulosic Biomass & other Renewable feedstocks. Several Indian institutes (IITs, IISC, IISERS, IICT, CSIR labs etc) and industries (PRAJ, Reliance, Bharat Petroleum, Abellon Clean Energies, Indian Oil, several start-ups supported by BIRAC etc) are involved in converting waste to value via fermentation and other technical routes.

United Kingdom

In the UK there has been significant interest in first generation bioethanol production plant e.g., from wheat (Vivergo) [24] and sugar beet [25] if there is sufficient appropriately costed feedstock. There are a number of relatively small and more recent industrial plants which have been developed which will use non-food-based biomass

[24] (https://vivergofuels.com/)
[25] (https://www.britishsugar.co.uk/about-sugar/our-factories)

resources e.g. Celtic Renewables[26] are using whisky wastes to produce butanol, LanzaTech are using waste gases from steel production to produce ethanol to be converted to jet fuel[27], while Fiberight are developing production of biofuel from sugars in MSW[28]. Stakeholders felt that in future, biofuel production from fermentation is likely to be directed at exploiting non-food resources which could include straw and other crop residues and renewable electricity either directly or via hydrogen, which has been taken into account in consideration of the research gaps/challenges presented here.

5.2 Fermentation Research Gaps

In order to build the full potential of fermentation for bioenergy and materials the following gaps require attention.

a. **Fermentation scale-up:** There is need for novel innovations in fermentation-based infrastructure, design of novel bioreactors that would facilitate optimisation abilities at larger scales. These should be embedded with the latest sensor technologies with smart monitoring of processes
b. **Further development of hybrid fermentation technologies for metabolic efficiency and higher value generation:**
    - Metabolic Flux Analysis guided optimisation of potential microbial strains leading to enhanced targeted fermentative products[29]
    - Hybrid chemical and bioelectrochemical modules for efficient conversion of feedstocks and subsequent fermentation
    - Scalable cell free systems for high value fermentative products[30]
c. **Multiple/Hybrid feedstock based scalable technologies are needed for economic viability:** Development of viable fermentative technologies that can simultaneously utilise treated precursors of Biomass (Agri, Food, Woody biomass etc) [31][8] with gaseous feedstocks (CO_2 recapture, H_2) needs proper research and deployment at various scales.
d. **Fermentation technologies aiming for multiple product recovery such as biofuels along with other higher value fermentative products:** There is need for R&D demonstrating pilot scale to commercial scale of fermentation processing involving advanced downstream processes for multiple product separation and recovery. Multiple products can be biofuels (CH_4, H_2, Ethanol, Butanol, Methanol etc) along with volatile fatty acids, biopolymers (like PHB,

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[26] (www.celtic-renewables.com)
[27] (https://lanzatech.com/)
[28] (https://fiberight.com/technology)
[29] Yao, R., Li, J., Feng, L. *et al.* ^{13}C metabolic flux analysis-guided metabolic engineering of *Escherichia coli* for improved acetol production from glycerol. *Biotechnol Biofuels* **12,** 29 (2019). https://doi.org/10.1186/s13068-019-1372-4

[30] Lim HJ, Kim DM. Cell-free synthesis of industrial chemicals and biofuels from carbon feedstocks. Curr Opin Biotechnol. 2022 Feb;73:158-163. doi: 10.1016/j.copbio.2021.08.002. Epub 2021 Aug 24.

[31] Oke, M.A., Annuar, M.S.M. & Simarani, K. Mixed Feedstock Approach to Lignocellulosic Ethanol Production—Prospects and Limitations. *Bioenerg. Res.* **9,** 1189–1203 (2016). https://doi.org/10.1007/s12155-016-9765-8

PHA and cellulose), biomolecules (like lactic acid, citric acid, succinic acid etc) and biomass for food, feed, and fertilizers. A techno-economic viability along with the environmental impact of these innovations needs to be undertaken.

e. **Energy Storage technologies that are scalable with efficient storage and transport:** Achieving a robust circular economy depends on an efficient last-mile delivery process. The biofuels produced via fermentative routes needs to be stored and transported with great efficiency that is scalable and environment friendly.

5.3 Opportunities for UK-India Fermentation Research Collaboration

Both UK and India are committed towards adopting multi-pronged approaches to meet Bioenergy needs in a sustainable manner. While there are region specific advantages and limitations both nations can leverage the ongoing and new partnerships to achieve ambitious targets of Bioenergy and new zero emissions. The following areas of common interests pertaining to the fermentation technologies to meet Bioenergy targets are proposed.

a. **Support proven and sustainable fermentative processes involving microbes** (individual or consortia based) for further scaleup. This can be bolstered by supporting novel innovations in bioprocess infrastructure with smart monitoring processes and optimisations that could lead to demonstrations from pilot scale to commercial scale
b. **Focus on hybrid fermentation technologies to achieve metabolic efficiency and generation of multiple higher value product**s. The research teams can leverage the latest advances of Metabolic Flux Analysis for better understanding the carbon flow of industrial chassis strains and assist in media optimisations and rational metabolic engineering. Specifically, efforts should be laid towards developing Metabolic engineering strategies to reduce metabolic burden of engineered hosts by ATP/NAD(P)H availability. Integration of MFA with process analysis (scale-up simulations, computational fluid dynamics) to understand cell's behaviour in dynamic bioreactor environment would ensure robustness that would help scaleup.
c. **Develop efficient ways to utilise multiple feedstocks in a scalable manner to derive Bioenergy and other valuables**. Integrating fermentation along with other technologies that can simultaneously use one or more of the following feedstocks (lignocellulosic waste, food waste, wastewater etc) along with gases (like CO_2, industrial flue gases or biomass gasification) for added value needs support. Focus can be applied to integrating fermentative processes with hybrid chemical and bioelectrochemical modules for efficient conversion of feedstocks and supplementation via renewably generated electrons.
d. **Technologies for multiple product recovery (downstream processing), Energy Storage** technologies that are scalable with efficient biofuel storage and transport also needs to be of high priority to realise circular economy model.

6. Gasification

6.1 Research Landscape

United Kingdom

The UK has a long history of development of gasification processes, first for coal and then for biomass, but tending to focus more on waste products, because of financial feedstock cost considerations. There was a large implementation initiative with the Arbre project in Yorkshire some 20 years ago. The well documented problems associated with that created a significant aversion to the technology amongst some participants for many years. A small number of universities continued to work on facilities. These include Leeds, Aston, UCL, Heriot Watt, Cardiff, Glasgow, Newcastle, Hull, Sheffield, and Bath. However, much of the activity is commercially focused with trial plants being supported first of all by policy mechanisms in the electricity sector, then in the transport fuel and heat sectors. All of these institutes have laboratory and pilot scale equipment where they can work with industrialists to develop and deploy technology.

Some work is funded by the national Supergen Bioenergy Hub e.g., ongoing work at University of Leeds and previously at Glasgow, Newcastle, and Bath, with other UKRI investments at UCL, Imperial College and Leeds. There is significant industrial funding via Innovate UK and BEIS and the UK participates in the IEA Bioenergy task on gasification. Key industrialists include Kew Technologies, Advanced Biofuel Solutions and Wood, who each take different approaches to gas upgrading, scale and energy application. In 2021 a comprehensive review of gasification performance was commissioned by BEIS, and a series of reports resulted[32] which clearly indicated significant unexploited potential and key status in terms of unlocking much-needed development pathways. Since then significant investment has occurred for a number of projects via the Net Zero Innovation Portfolio, including greenhouse gas removal projects and hydrogen BECCS pathways using gasification[33].

An interesting recent trend (perhaps driven by renewed focus on hydrogen and CO2 removal) has been emphasis on pressurized gasification units, including fluidized beds.

India

India has deployed high numbers of gasification facilities in rural areas focused on rice straw, husks, and similar residual feedstocks. These are often linked to reciprocating engines to provide power in remote rural areas. There are many links with universities and technological institutes delivering good understanding of the engineering and practicalities of biomass gasification.

Institutes of technology have significant expertise in this area with several operating gasification demonstration plants of different types and scales. Often there is close

[32] Advanced Gasification Technologies Review and Benchmarking: summary report (publishing.service.gov.uk)
[33] Net Zero Innovation Portfolio - GOV.UK (www.gov.uk)

collaboration with industrial partners with significant operating expertise and this seems anecdotally to accelerate innovation towards smoother deployment. However, the end-focus and reliability of these plants is not entirely clear.

Both countries seem to be making progress but are still seeking effective means of navigating the scale-up and innovation pathways to commercialization, which are frequently discussed at meetings of the International Energy Agency Bioenergy gasification task (which has been attended by both countries as well as a small number of others in recent years: including Sweden, U.S., Netherlands, China).

6.2 Research Gaps and Challenges

There are many challenges facing deployment of gasification. Most focus around upgrading of the raw syngas to reduce tar content, but also to reduce particulate carry-over and inorganic species, particularly when these contain high quantities of alkali earth metals such as potassium (well known to cause fouling), acid gases such as chlorides (known to cause corrosion), particulates that cause erosion and have environmental and health impacts.

In some cases, individual plants have been configuring to operate in a way that avoids problems, but the underpinning scientific understanding of how/why this is the case remains poor. In addition, there is significant interest in the UK in net negative gasification configurations, for which CO_2 removal from pressurized syngas using inexpensive materials is a key challenge.

6.3 Potential for UK-India Collaboration

There is significant potential for information exchange and visits between both countries to support learning around:

- Tar removal/reduction using thermal, catalytic and plasma techniques
- Inorganic species removal from syngas via hot gas cleaning
  Design and scale-up experience and design

In the UK, biomass gasification programme started with much enthusiasm but could not garner serious attention from the Govt. However, recently the UK Government and private companies are again engaging and prioritizing biomass gasification. In India, kilowatt (kWe) level biomass gasification for rural and remote area electrification is more popular than large scale centralized plants. Overall, there is a mixed success of biomass gasification and biomass combustion programmes in India. The Indian Institute of Technology, Bangalore is a prominent academic institute in India to develop indigenous biomass gasification technology. There are also private companies, experts in manufacturing biomass gasification units. Biomass cogeneration, especially sugarcane bagasse cogeneration in the sugar factories of India is a successful programme. In fact, bagasse cogeneration supports a major share of India's biomass power programme.

7. Biorefinery and Chemicals

Overcoming energy poverty with renewable and clean energy is critical in enabling uninterrupted energy access for nurturing development. Equally important is the *sustainable production of materials and chemicals*. The unprecedented growing demand for sustainable energy and chemicals can be effectively met by exploiting and maximising the use of biomass resources. In this aspect, *biorefineries, offering a multi-product platform* is beneficial and will pave the way toward net-zero emissions. This section specifically discusses the status of biorefineries in the Indo-UK perspective, the research gaps and the research need to bridge these gaps.

7.1 Research Landscape

India and the UK have set ambitious targets for achieving net-zero emissions [34][35]. Whilst the size and scale of the implementation may vary between the two countries, the *nature of research and technological advancements* required to achieve the (inter)nationally important net-zero perspectives is quite comparable. The multi-product biorefinery platform is therefore attractive and has gained mileage. The recent round of Newton-Bhabha Industrial Waste Challenge jointly funded by Innovate UK and DBT is a key example[36]. The challenge involved research and development focusing on the recovery or manufacture of valuable materials from wastes derived in sectors of leather/tanning/textiles, municipal solid waste, paper and pulp, sewage, and sugarcane.

Stakeholders

Some of the key institutions (representative, not exhaustive) in both these countries that have been focussing on this area are shown in Table 1.

Table 1: List of some of the key institutions working on biorefineries in India and the UK.

Some key institutions in India	Some key institutions in the UK
• Indian Institute of Technology(s) (IITs) • Indian Institute of Science (IISc) • Institute of Chemical Technology (ICT) • Indian Institute of Petroleum (IIP) • National Environmental Engineering Research Institute (NEERI) • Vasantdada Sugar Institute	• Imperial College London • Aston University • University of Leeds • Queens University Belfast • University of Manchester • University of York • University of Surrey • University of Bath • University of Southampton

[34] Prime Minister's Office Statement by Prime Minister Shri Narendra Modi at COP26 Summit in Glasgow. https://pib.gov.in/PressReleasePage.aspx?PRID=1768712

[35] BEIS UK Net Zero Strategy: Build Back Greener. https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/1033990/net-zero-strategy-beis.pdf

[36] DBT India; Innovate UK India-UK industrial waste challenge. https://dbtindia.gov.in/sites/default/files/India-UK-industrial-waste-challenge-2017_Call_for_Proposal_0.pdf

• CSIR labs • Vellore Institute of Technology (VIT) • BITS-PILANI • Jawaharlal Nehru University (JNU) • University of Delhi	• University of Nottingham • John Innes Centre • Cranfield University • University of South Wales • Aberystwyth University • University of Edinburgh • Heriot-Watt University • University College London • Newcastle University • Liverpool John Moores University • University of Liverpool • Lancaster University • Robert Gordon University • Sheffield Hallam University • University of Greenwich

Besides the academic institutions leading research projects, industries also are at the forefront of co-leading and deploying new technologies. Some of the industries that have been in this space recently in India and the UK are listed in Table 2.

Table 2: List of some of the industries working on biorefineries in India and the UK.

Industries in India	**Industries in the UK**
• ONGC • IOCL • HPCL • BPCL • Praj • Vivira • Several start-ups supported by DBT BIRAC • India Glycols Limited • GPS Renewables Private Limited • String Bio Private Ltd	• FibreRight • BioSep Ltd • Lixea • FibreLean • James Cropper • Inspro • Moolec • Green Fuels Research • Nova Pangea Technologies • Celtic Renewables • Vivergo • British Sugar

Areas of Interest

The plethora of platform chemicals (and fuels) that can be produced in a biorefinery is dependent on two factors – *the feedstock and the valorisation pathways*. Whilst the feedstock determines the amounts of fibre fractions available for processing, the valorisation pathways control the product portfolio.

A feedstock is the primary critical factor that controls successive unit operations involved in its processing. The general interest within the research community as well as the industrial stakeholders is to utilise *'waste biomass' as 'resources'* to ensure that biorefining is truly circular. Waste biomass utilised can be further broadly classified under three categories namely – agri and forest residues (e.g., rice straw, flower waste), industrial waste (e.g., paper and pulp waste, sugar industry waste such as bagasse, spent wash, press mud) and municipal/domestic waste (e.g., wastewater, sewage sludge, food waste, fish waste, oils/fats).

Valorisation pathways for biorefineries generally fall under two categories, namely – biochemical and thermochemical routes. Biochemical routes include classical fermentation (e.g., solvent/acid fermentation, anaerobic digestion) while thermochemical routes include catalytic valorisation, pyrolysis, gasification, and torrefaction. In addition, third generation (3G) biorefineries that convert CO_2 and renewable feedstocks (e.g., microalgae and seaweed) into fuels and chemicals using cellular hosts are also gaining attention[37].

Using a combination of both these factors, several products beyond biofuels have been targeted. These include (but are not limited to), volatile fatty acids, food/pharma ingredients, bioplastics, nitrocellulose, ash as concrete binders, animal protein, activated carbon, lactic acid, citric acid, succinic acid, xylitol, furfural, HMF and fragrances.

7.2 Research Gaps

The successful commercialisation of biorefineries is the ultimate goal. Several research gaps (all of them linking back to maximising biomass conversion) have been already identified by the research community and are being investigated to bridge these gaps towards scale-up. Some of the important gaps are currently being addressed, but require more investigation as discussed below.

A scalable and efficient pre-treatment process is an urgent need: Biomass has a highly complex structure leading to its recalcitrance. Pre-treatment is therefore essential to improve the (bio)availability and utilisation of the fibre fractions for effective valorisation. It has been estimated that ~40% of the operating costs are required for pre-treatment[38]. The current investigation in this area spans around identifying innovative, efficient, cost-effective methods (e.g., hydrodynamic cavitation, advanced microwaves, ionic liquids/deep-eutectic solvents). However, scaling up pre-treatment technologies with promising techno-economic feasibility requires more focus [39].

Process integration leading to multiple products should be a priority: Integrating biochemical and thermochemical routes to produce multiple products is of interest (e.g., acid/solvent fermentation followed by biogas generation from residues). However, for maximising the biomass conversion it would however be necessary to identify other routes (e.g., physical routes) that could be integrated. For example, one of the Newton-funded projects looked at the possibility of utilising rice husk ash (upon protein and carbohydrate extraction) as concrete binders for the building industry. With the research and technology pool in India and the UK progressing

[37] Liu, Z.; Wang, K.; Chen, Y.; Tan, T.; Nielsen, J., Third-generation biorefineries as the means to produce fuels and chemicals from CO2. *Nature Catalysis* 2020, 3, (3), 274-288
[38] Yang, B.; Wyman, C. E., Pretreatment: the key to unlocking low-cost cellulosic ethanol. *Biofuels, Bioprod. Biorefin.* 2008, 2, (1), 26-40
[39] Galbe, M.; Wallberg, O., Pretreatment for biorefineries: a review of common methods for efficient utilisation of lignocellulosic materials. *Biotechnol. Biofuels.* 2019, 12, (1), 294

swiftly on the solar front, integrating photovoltaic or photo(electro)catalytic valorisation routes and biochemical routes including the 3G biorefinery model of fixing atmospheric CO_2 in a scalable mode could be investigated.

Lignin valorisation for maximising overall biomass conversion efficiency: Feedstock heterogeneity is inevitable when dealing with biomass. Especially, lignin present in the biomass is known to be recalcitrant to biochemical valorisation. Thermochemical and catalytic valorisation routes have been the preferred pathways to extract value out of lignin. With standalone cellulose and hemicellulose valorisation routes established, extensive research is required in this specific area of lignin valorisation as it has the potential to maximise the overall biomass conversion efficiency.

Allied areas of significance: Other areas that need more attention include life cycle assessment, socio-economic and techno-economic impact analysis, re-imagining the design and scale-up of processing plants, kinetic and process modelling, use of non-critical raw materials for the development of catalysts, identifying regional waste biomass resources as feedstock for biorefineries, product separation technologies and transforming existing sectors/industries to biorefineries (e.g., anaerobic digestion based biorefineries).

7.3 Collaborative Research Opportunities

A combination of feedstock, valorisation pathways and product streams will need to be carefully analysed to determine the feasibility of the biorefinery. To reiterate, the three most important areas that need immediate attention to progress the field of biorefineries in both India and the UK are as follows:

- Identifying scalable and sustainable pre-treatment methods to elevate the process TRL levels.
- Addressing feedstock heterogeneity for maximising biomass conversion (enhanced product yield/tonne biomass).
- Innovative process integration for maximising biomass conversion.

Appendix A: Bioenergy Research Activities, Programmes and Mechanisms in India

A.1 Primary Research Funders

Research scholars and students in India, interested in research including but not limited to the field of bioenergy, have numerous sources of funding. The most common source is their institution/University. Indian Institutes/Universities obtain their funding from several governmental/private organizations and a majority of these are project specific grants. Thus, researchers can benefit from such collaborations. The government of India has statutory bodies (Like SERB, DST, MNRE, etc.) which have various schemes to support scientists and faculty for conducting research. The schemes range from stipends, grants to travel support for international conferences.

Science and Engineering Research Board-Department of Science and Technology has authorized a number of grants either in the form of scholarships or fellowships for interested researchers and faculty who desire to conduct research in the areas of Science, Technology, Engineering, Agriculture and Medicine. [26]

SERB has also over-time collaborated with several international bodies to promote quality and independent research amongst doctorates as well as other scientists. There are numerous scholarships and fellowships that support Indian nationals for conducting research at a university/ institution abroad, particularly in STEM.

The Ministry of New and Renewable Resources (MNRE) is yet another initiative by the Government of India in the form of a platform that recognizes the need for new and renewable sources of energy. Apart from funding for research in bioenergy and biogas; MNRE has come to various scientists' aid for funding. "Development of hybrid high rate biomethanation reactor with locally available media for treating waste water and solid waste" and "Development & performance evaluation of a 3 kW Biogas based power generation system utilizing Lignocellulosic biomass" were recently completed at Tamil Nadu Agriculture University and IIT Guwahati respectively. "Development of a suitable pre-treatment system for paddy straw disintegration for biogas generation leading towards commercialization of technology" is an ongoing project at Centre of Rural Development, IIT Delhi. A student/ research group, with principal and co-principal investigators may submit a proposal with an estimate of the total of the expenditure associated with the project along with other details. [27]

The Department of Science and Technology (DST) has been supporting researchers and scientists in many ways. Amongst its many schemes, DST launched Scheme for Young Scientists and Technologists (SYST). The objective of the scheme was to encourage young scientists and technologists who have a zeal to work with the society to provide scientific solutions to the existing/futuristic problems and to foster innovative ideas having direct bearing on society, as well as visible technology transfer components. Young researchers affiliated to an NGO or institution (for infrastructural and scientific support) submit their proposed research project to DST, SEED division.

DST has a number of ongoing and future programme for bioenergy and related research spectra such as Bio-Integration of Agricultural Activities and Resource Management (BIOFARM); Land, Biomass and Water Management; Rural Energy Program for non-grid areas and Pilot demonstration and dissemination of rural technologies. [28]

ICAR is one of the biggest funders of research projects of agricultural and bioenergy related projects. A researcher or a group of researchers preferably from a group of institutions: public, private, CGIAR or civil society can submit a proposal for a project with the amount funds required be no less than INR 2 crore. ICAR has invested in numerous bioenergy related projects across different institutions (Example: IIT Kharagpur, IIS, TNAU, etc.) [29]

All India Council for Technical Education (AICTE) has a Doctorate Fellowship (ADF) with the motive to promote research culture in AICTE approved institutions, to promote collaborative research between institutions and industries leading to start-up and to nurture talents for technical research. There are several broad thrust areas for research enlisted by AICTE; among these are Green Technologies, Energy Production and Storage, Energy Efficiency, Renewable and Sustainable Energy, Smart Technologies for Agriculture and Food Industry. The duration of fellowship is typically three years and the fellowship amount is INR 30,000 for the first year and INR 35,000 for the third year (HRA is variable). AICTE also has a research grant scheme called Collaborative Research Scheme to provide research grants for young TEQIP faculties recruited in different TEQIP institutes. Maximum amount of funding is INR 25 Lakhs.

A.2 Key Research Programmes

The bioenergy sector in India is currently primarily driven by Government of India's initiatives. Key government ministries such as the Ministry of New and Renewable Energy (MNRE) and the Ministry of Environment and Forests (MoEF) have had a significant role in promoting bioenergy. A myriad of programmes and projects are actively being undertaken by the Government bodies as well as some industries whether it is Central Salt and Marine Chemicals Research Institute (CSMCRI) pursuing research in the field of molecular biology and biotechnology to understand and utilize the potentials of coastal and marine bioresources [17]; developing bio-energy and biofuels for defence purposes by the Defence Institute of Bio-Energy Research (DIBER) [18]; installing first continuous Steam Explosion pilot plant & Extractor system (300 kg/day) by DBT-IOC centre for Advanced Bioenergy [19]; biofuels and biomass cook stoves by Sardar Swaran Singh National Institute of Bio-Energy [19]; improving efficiency of cellulase enzymes for hydrolysis of pre-treated biomass to produce sugars which is further used as a feedstock for ethanol production at ICGEB [21]; algal biofuels at the DBT-TERI Centre of Excellence in Advanced Biofuel and Bio-commodities [23] or advanced biofuels for transportation and industrial application at Department of Science and Technology. [24]

Indian Agricultural Research Institute's recent research in biomass, algal fuels and microbial biofuels, fermentation suggests active involvement in bioenergy and related research. [25] Some of the recent projects were in the areas of agro-residue and biomass management, production and processing of micro-algal biomass for biodiesel. Indian Council of Agricultural Research (ICAR) has been yet another research centre working on waste management by microbial decomposition, production of microbial biomass, agro residue and biomass feedstock for hydrogen production, and more. [30] Council of Scientific and Industrial Research (CSIR) on the other hand has enlisted multiple thrust areas of research across several disciplines including aerospace, civil engineering, biotechnology, chemicals and petrochemicals, energy and many more. [31]. There is numerous bioenergy related ongoing/completed projects. Few of them are listed in the appendix.

The Government of India has also launched several schemes and made funding commitments for different projects to address climate change and the need to shift to renewable and alternative energy such as the biogas thermal/off-grid programme; energy from urban, industrial and agricultural waste/residue; biomass based cogeneration in sugar mills and other industries in the country; New National Biogas and Organic Manure Programme (NNBOMP) managed by the Ministry of New and Renewable Energy; National Policy on Biofuel of 2018; Sustainable Alternative Towards Affordable Transportation is a scheme by Ministry of Petroleum and Natural Gas (MoPNG) and many more. The relevant details on some of the schemes are elaborated in the appendix.

Figure 1: IOC- Clarus Bioenergy Pvt Ltd.

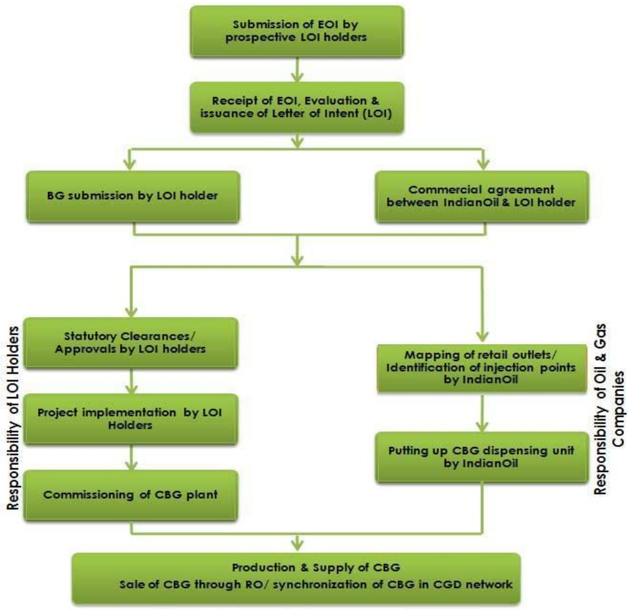

Figure 2: Process involved in Setting up a BGC Plant Under SATAT

A.3 Major Research Institutes

Not only is the government involved in promoting bioenergy as a substitute for fossil fuels, but also multiple Indian universities have been investing in bioenergy research across the country. There has been some very valuable research done in all the defined thrust areas across which the UK and India could work together.

Indian Institutes of Technology (IIT) along with some other universities have numerous ongoing or successfully incorporated bioenergy projects. For example, the Department of Hydro and Renewable Energy (HRED) at IIT Roorkee has been actively working on biochar and biomass-based projects. [2] Some of the recent projects are Stubble management using decentralized torrefaction systems for biochar-based fertilizers; Pyrolysis of residual biomass for resolving energy and water issues and Sustainability assessment of ethylene production from biomass. IIT Guwahati has a bioenergy lab as well as a biofuel lab with a focus on biochar, biofuel, and genetic engineering of clonal plants. [4,5] The main research activities include genetic engineering of biofuel plants and crops, bioprocessing, microalgae-based biodiesel production, conversion of sugar to fuels and chemicals, and more. The DBT Pan-IIT Centre for Bioenergy at IIT Bombay has brought together scientists from other IITs to work on innovations in the field of bioenergy and green energy solutions.

There are several groups within the department which are associated with different bio-energy related research. [9] The research interests of these groups are namely Cyanobacterial biofuels; algal biofuels; biochemical, thermochemical, and electrochemical Conversion; and bioreactor designing. IIT Madras has always been a pioneer for research and development in the fields of bioenergy and sustainability. In 2020, a research team worked on a project titled, “High Energy Bio-Oil from Agricultural and Plastic Wastes “. The agricultural wastes included rice straws and bagasse. The project was funded by Gail Ltd. The faculty at IITM have bioreactor analysis, catalytic pyrosis, etc. as some of the research interests. IIT Kharagpur has P.K. Sinha Centre for Bioenergy and Renewables dedicated to research in the field of bioenergy and biotechnology.

Apart from the research centre, Agriculture and Food Engineering & Energy Science and Engineering department have continuously proven interest in collaborative as well as interdisciplinary research related to biofuels and biomass.[10] Some of the current projects include Enhanced 2G Bioethanol Production; Pilot Scale Production of Ethanol from Lignocellulosic Feedstock; Improved Production of Fatty-acid Derived Biofuels and Chemicals. IIT Kanpur is involved in utilization of biofuels, characterization of fuel and performance, emission and durability investigations of the engines, and vehicles. Engine research laboratory (ERL) developed a hardware, which is cheap, and it allows the engine to operate on straight vegetable oils for long duration without any operational and durability problems. Engine research laboratory also developed its own design of a biodiesel pilot plant with a production capability of 30 litres per batch, which amounts to approximately 200 litres per day and can be used by semi-skilled workers and villagers. An extensive investigation on transport engines has been done in ERL to replace petro-diesel with biodiesel.

Interdisciplinary Centre for Energy Research (ICER) at Indian Institute of Science (IISc) recognizes biomass and alternative fuels for their research potential and as national interests. ICER has received funding from DST, MNRE, Indo-US Science and Technology Forum and Karnataka Government. A MoU has been signed between IISc and Homi Bhabha National Institute (HBNI) for carrying out joint research and educational activities in the field of energy. Centre for Renewable Energy and Environment Development (CREED) at BITS Pilani has been actively doing research on Biomass Gasifiers and plans to work on Design optimization of biogas- based turbines and engines in the near future. [14] Some of the research topics/projects include production of hydrogen-rich fuel gas from Jatropha residue cake; biomass pyrolysis & product characterization; and biofilm reactors. Savitribai Phule Pune University (SPPU) promotes interdisciplinary research, development, and teaching activities in the field of energy and renewable energy sources. Primary thrust areas include biomass and biogas. [16] Amongst other research labs, Institute of Chemical Technology (ICT) has a Centre for Energy Biosciences which works over a wide range of research areas, one of which is: bioenergy, biofuel, and biomass to other biochemicals or high value organic/inorganic chemicals. Other labs also conduct cross-functional research like recycling of plastic and industrial wastes, fermentative production and downstream processing of enzymes/metabolites, green Chemistry & technology, and several others. [54]

A.4 Industrially Focused Research

In 2019, the Indian economy was the world's fifth largest by nominal GDP and third largest by purchasing power parity. This can be substantiated by the fact that in 2021, there were more than 1.1 million active companies in India out of which, 7 companies were listed in Fortune 500. Interestingly, 4 of these companies are working in the energy sector. These were: Reliance Industries, Indian Oil Corporation, Oil and Natural Gas and Bharat Petroleum. Most of these as well as other large companies have independent R&D centres which are pursuing research in bioenergy and biofuel. Some of these companies and their research activities are elaborated in this section.

Corporate Research and Development Centre, Bharat Petroleum (BPCL) collaborated with Boston Consulting Group and formed a new research framework in 2017. The objective of this new framework is to pursue various R&D domains with different optimal research strategies. BP has state of the art research facilities and labs such as analytical lab, biofuel lab, catalyst lab, residue upgradation lab, Engine & alternate energy lab amongst some others. The labs are involved in cross-functional research in bioenergy including production of biofuels, biochemicals and bioprocesses, and biomass gasification. The facilities at the biofuel lab include technologies for fermentation, molecular biology, biomass pre-treatment, and more. [32]

Figure 3: Source: Bharat Petroleum

In 2017, BPCL collaborated with Odisha University of Agriculture to develop and promote rice straw-based biofuel production in the state. The company provided a funding of INR 5 crores to the university for effective utilization of paddy straw for biofuel production in a biochemical enzymatic process.

In January 2022, the company announced an investment of INR 25000 Crores to develop its renewable profile. The company aims to build a renewable energy capacity of 10 Gigawatts (GW) out of which biomass-based energy is 40 MW. The company has collaborated with BARC to scale up alkaline electrolyser technology for green hydrogen production.

Another Fortune 500 company, Indian Oil's business interests encompass the entire hydrocarbon chain. Indian Oil R&D is pioneering work in promising & futuristic alternative energy segments like Bioenergy, Solar Energy, Hydrogen, Energy Storage, Battery, CCU Technologies etc. IOCL has developed a new and economical enzymatic pre-treatment process at pilot level using agriculture waste and is now scaling it up in a demo plant at Panipat. IOCL R&D is also working on a bio-route to convert the CO_2 from refinery flue gasses to Ethanol by installing India's first of its kind CO_2 to Ethanol production plant at Panipat.

Indian Oil has developed a two-stage anaerobic process for converting various types of organic wastes to biogas with ability to produce 15-20% more methane than other contemporary technologies and higher gas yield. Transportation of neat Biofuel and its blends, compressed Biogas as well as carbon dioxide through cross country pipeline are identified for research work in near future at IOCL [33]

Figure 4: DBT-IOCL enzymatic pre-treatment Pilot Plant

In 2021, an ocean farming start-up company called Sea6 Energy left everyone amazed as it raised $9 million in funding for its seaweed- based technologies. Sea6 is indulged in exploration and production of several products obtained from seaweed whether it's animal feed, bio-polymer, biofuel or food ingredients. Sea6 has conceptualized a unique process that uses hydrothermal liquefaction to replicate the fossil fuel process in a matter of minutes, creating biocrude produced from sea plants. The resultant fuel is carbon neutral, sustainable and at scale. It is commercially viable and finds its application in refineries. Sea6 has partnered with various companies/ institutes as well. Some of these are TATA Capital, Novozymes, Mahindra, ICAR, etc. [34]

Figure 5: Source: Sea6 Energy

Gail (India) Limited is one of India's leading natural gas companies. Gail is also expanding its business interests in renewable energy technologies Gail has taken several initiatives to practice a more sustainable mode of business. From waste management to start-up support, it is a leading company when it comes to sustainability. Gail has successfully produced manure from biodegradable waste for horticulture maintenance Mansarampura/ Sanganer plants and Jaipur Head Quarters.

GAIL's Start-Up initiative 'Pankh' was launched to build a strong eco-system for nurturing Innovation and the spirit of entrepreneurship. It has set aside a corpus fund of INR 50 crore to invest in start-ups. GAIL had signed investment agreements worth INR 22 crore with 9 Start-Ups in FY 19-20. [35] Gail has signed an MOU with IIT Madras and IIM Lucknow to provide funding for start-ups that share the same vision as that of Gail. Some of the key focus areas are City Gas Distribution, Gas Sourcing and Optimization, Renewable and Alternative Energy Sources and more. [36] In 2020, the chemical engineering department at IIT Madras used agricultural wastes such as rice straws and sugarcane bagasse and other plastic wastes to make biofuel. This research project was funded by Gail Limited. [37]

GAIL Gas Limited, a leading City Gas Distribution Company, is poised to accelerate City Gas Distribution business in a focused manner in various cities across the nation. Petroleum and Natural Gas Regulatory Board (PNGRB) has authorized GAIL Gas to implement CGD Projects across several cities/municipalities in the country [35]

Figure 6: Source: Gail Gas Limited

Hindustan Petroleum Corporation Limited (HPCL) has undertaken various biofuel projects in the country including Compressed Biogas (CBG) Projects under SATAT (Sustainable Alternative Towards Affordable Transportation) initiative of Govt. of India which envisages target production of 15 Million Metric Ton (MMT) of CBG by 2023-24, from 5000 CBG Plants. [38]

Abellon Clean Energy is a leader in waste to energy with experience of over a decade of generating renewable energy from urban and agricultural wastes. Abellon has partnered with civic bodies to develop city waste processing and disposal projects in key cities of Gujarat to process and dispose 50 –100% of the waste generated.

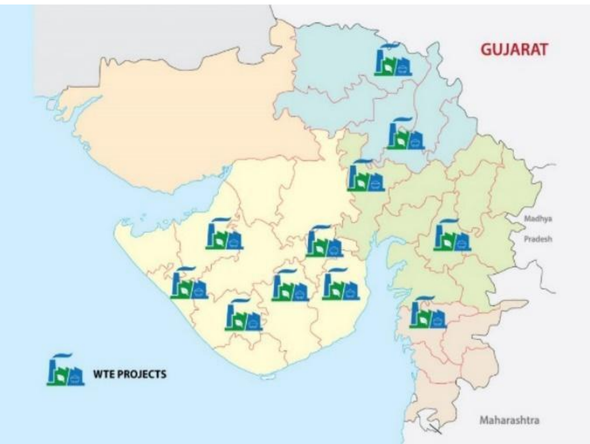

Figure 7: Abellon: Waste to Energy (WTE) Projects Across Gujarat

Abellon also has a wide range of eco-friendly, carbon neutral solid biomass pellets, and eco-friendly equipment that can effectively replace LPG, Diesel and other fossil fuel-based systems. Abellon is setting up a network of facilities to generate

Compressed Biogas, starting with key cities of Gujarat. The facilities are designed to harness a wide variety of waste including agriculture residue, cattle dung, sugarcane press mud, municipal solid waste, sewage treatment plant waste. [39]

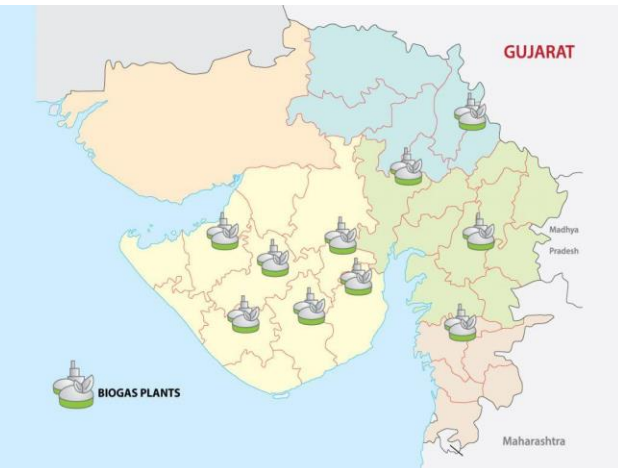

Figure 8: Biogas Plants Across Gujarat by Abellon

A.5 Research Funding Mechanisms

India has partnered internationally with several countries in order to accommodate their shared goal- Net Zero Target by 2050. The Prime Minister of India announced the aim of India becoming carbon neutral by 2070 at COP26 Climate Crisis Summit in Glasgow. Bioenergy is a common thrust area amongst a majority of the collaborations (for example: US-India Strategic Clean Energy Partnership, India EU Joint Committee, International Science and Technology Cooperation, etc. There exists some well-established funding mechanisms for UK-India collaborations or projects.

Newton U.K.-India Industrial Waste Challenge is a partnership between UK Research and Innovation (UKRI) and Department of Biotechnology, Government of India (DBT). It supports multidisciplinary research collaborations between the academic and industrial communities based in the UK and India. Research and development projects focus on using cutting-edge bioscience, chemistry, and engineering solutions to reduce industrial waste and pollution in India. The conversion of industrial waste into multiple useful products (a biorefinery approach) will allow for improved value recovery from waste, reducing the amounts needing disposal or being released into water courses. There are several projects funded and undertaken as a part of the partnership with individual project partner institutions and companies, representing a joint UK-India investment of £10 million. [55]

Newton fund is yet another funding authority. It builds research and innovation partnerships with countries in Africa, Asia, and Latin America to support economic development and social welfare, tackle global challenges and develop talent and careers. It does this through equitable partnerships with middle-income countries, multidisciplinary research based on agreed national strategies and nurturing talent and careers with capacity development. India is one of the partner countries amongst several others (Brazil, China, Colombia, Egypt, and many more). The Newton Fund is managed by the UK's Department for Business, Energy, and Industrial Strategy. The fund is delivered through UK partners who offer tailored research and innovation programmes in partnership with governments and organizations in each Newton Fund partner country. [55]

Managed by Newton Fund, is the Newton prize (2017-2020) which embraced outstanding international research partnerships between the UK and Newton Fund partner countries. The annual £1 million funding prize enabled international research partners to continue working together to address some of the world's most pressing health and development issues such as malaria, antimicrobial resistance and climate change. India was one of the countries to win the Newton Prize in 2017. The project titles were "Advancing the Efficiency and the Production Potential of Excitonic Solar Cells" and "Evaluation of the introduction of a novel device in the management of hypertension and shock in pregnancy in low resource settings". [55]

Figure 9: 2020 Newton Prize Committee Chair: Prof Alice Gast

A.6 SERB's Schemes for Researchers

1. Prime Minister's Fellowship for Doctoral Research: The Prime Minister's Fellowship is a joint funding scheme by the Government of India and a partner Industry. The scheme has the provision to award up to 100 new scholarships every year, of up to Rs 8.7 lakh per annum per candidate. This means, a monthly stipend of between Rs 55,000.00 to Rs 72,800.00 depending on HRA. As per the provisions of the scheme, as approved by the Department of Science and Technology, the scholarship is given for a maximum period of four years. 50 % of the funding is provided by the government and the other 50% by the partner industry.

2. Abdul Kalam Technology Innovation National Innovation Fellowship: SERB in association with Indian National Academy of Engineering, initiated the fellowship program to recognize, encourage and support translational research by Indian Nationals to achieve excellence in engineering, innovation and technology development. The initial duration of fellowship is 2 years and a possible extension for up to 2 more years based on the performance.

3. Early Career Research Award scheme: The scheme aims to provide quick research support to the young researchers who are in their early career for pursuing exciting and innovative research in frontier areas of science and

engineering. It is a one-time award with grant up to INR 50 lakhs (excluding overheads) for a period of three years.

4. SERB Women Excellence Award: SERB Women Excellence Award is a one-time award given to women scientists who have received recognition from any one or more of the national academies such as Young Scientist Medal, Young Associate etc. If qualified, the women researchers will be supported with a research grant of Rs.5.00 lakh per annum for a period of 3 years.

5. SERB-National Post-Doctoral Fellowship: The SERB-National Post-Doctoral Fellowship (N-PDF) is aimed to identify motivated young researchers and provide them support for doing research in frontier areas of science and engineering. The fellowship amount may be up to INR 55,000 and the research grant is INR 2 Lakhs (excluding overheads).

6. SERB – POWER (Promoting opportunities for Women in Exploratory Research): SERB-POWER program is formulated to mitigate gender disparity in science and engineering research funding in various S&T programs in Indian academic institutions and R&D laboratories. SERB – POWER is specially designed to provide structured effort toward enhanced diversity in research to ensure equal access and weighted opportunities for Indian women scientists engaged in research and development activities. The funding could be either a fellowship or grant but not at the same time.

7. Start-up Research Grant: The Start-up Research Grant (SRG) scheme aims to assist researchers to initiate their research career in a new institution. It is a two-year grant meant to enable researchers working in frontier areas of science and engineering to establish themselves and move on to the mainstream core research grant. The research grant is of INR 30 Lakhs plus overheads for a period of two years.

8. Core Research Grant: This scheme encourages emerging and eminent scientists in the field of science and engineering for individual centric competitive mode of research funding. The scheme provides core research support to active researchers to undertake research and development in frontier areas of Science and Engineering.

A.7 Research Projects in Government Statutory Bodies

There are several Government statutory bodies which are developing cross-functional and interdisciplinary technologies to replace the current conventional energy resources with more efficient and sustainable sources of energy. This section of the appendix elaborates on the research/projects of some of these centres.

Central Salt and Marine Chemicals Research Institute (CSMCRI) is working on the following research areas:

- Cytochrome genes for enhanced photosynthesis and biomass: Genes encoding cytochromes were cloned from seaweeds and over-expressed in tobacco for enhanced photosynthesis and biomass. Transgenic analysis showed these genes as potential candidates for genetic engineering to enhance the growth and biomass production in crop plants.

- Generation of energy from microalgal feedstock through CO2 capture from flue gasses: The biomass productivity increase from 8 g m^{-2} d^{-1} to 13 g m^{-2} d^{-1} was observed during December 2019 to March 2020. This endeavour aimed to provide a growth profile of microalgae cultivated at the vicinity of flue gas chimneys and that knowledge could be used as leverage for power plant integrated development of microalgae-based biodiesel feedstock and by-products.

DIBER's research accomplishments are as follows:

- DIBER has introduced a biofuel crop, Camelina sativa, in India. Research is in progress to develop energy solutions in the form of polyols, dielectric fillers, hydroxyl fatty acids as a precursor for the synthesis of novel products from camelina oil.

- The institute has taken up R&D in developing technologies for processing of forest plant residues such as pine needles and municipal waste (polythene-HDPE & LDPE) for obtaining useful energy.

- R&D is also in progress for finding biofuel/ bioenergy solutions using native algae of border areas of Uttarakhand.

Some of the research activities at Sardar Swaran Singh National Institute of Bioenergy are:

- Biomass management i.e., harvesting, collecting, transportation, storage, and pre-conditioning studies.
- Technology development for the production of bio-ethanol using lingo-cellulosic materials, especially the agricultural crop residues and its application.
- Technologies development relating to thermal conversion of biomass such as gasifier designing/fabrication, combustion of biomass and power generation, biomass pyrolysis and the performance evaluation of the systems and economic appraisal.
- Technology development for production of Bio-oil/lignoil, bio-crude production and integrated bio-refinery development.
- Establishment of testing centres for chulhas for domestic applications, Biomass Thermal Gasifiers, and other renewable energy devices.
- Generation of biogas from animal excreta and agricultural wastes, purification of the Bio-gas, its bottling and commercial application of both carbon dioxide and Methane.
- Hydrogen generation from biomass resources (using producer gas and biogas both generated from biomass).
- Study on the growth characteristics of different varieties of oil-bearing plants such as Jatropha Curcas and others.
- Development of Bio-diesel production parameters using non-edible and waste oils, different types of catalyst, feed stocks and the use of bio-diesel as fuel in diesel engines.

- Demonstration of various renewable energy devices such as biomass gasifier, briquetting plant, biogas-power plant, etc. in the campus and meeting 100% power requirement of the Institute using renewable energy devices.
- Design, development and installation of biogas & solar based 5 TR Hybrid Vapor Absorption Refrigeration (HVAR) systems for heating and cooling applications.

DBT-ICT Centre for Energy Biosciences has various research groups namely:

- Green/Chemical Catalysis
- Enzyme Technologies
- Fermentation Technologies
- Algal Technologies
- Synthetic Biology
- IP Management Technology and
- Commercialization Unit and Separation Technologies.

DBT-ICGEB Centre for Advanced Bioenergy Research has four broad areas of research:

- Genomics: Analysis of function and structure of genomes to synthesize novel and efficient hydrolytic enzymes from bacteria, yeast, fungi, and algae cells.
- Systems Biology: Investigating cellular behaviour and metabolism at systems level through integrated analysis of high throughput OMICS data as well as genome scale metabolic models.
- Synthetic Biology: Integrating system biology and molecular biology approach to improve biomolecules to enhance biofuel production.
- Fermentation Technology: End to end process development for biofuel production

DBT-TERI Centre of Excellence in Advanced Biofuel and Bio-commodities is working on development of sustainable next generation feedstock (algae biomass) and aquatic plant (*Azolla* and water hyacinth) to use as platform feed for production of advanced biofuels (algal biodiesel, biohydrogen, and pyrolytic bio-oil). Under this, the centre aims to:

- Set up an indigenously designed 100,000 litre algal photo-bioreactor growth-harvest system at a coastal location in Mumbai
- Large scale cultivation of *Azolla* in wastewater with a goal to recover nutrient from waste and generate value added biomass to use as feed for biohydrogen production
- Manage water bodies from invasive water hyacinth through collection of these biomasses to use feed for biohydrogen production

The centre is also exploring production of three forms of advanced biofuels – algal biodiesel, biohydrogen and pyrolytic bio-oil – from next generation feedstock.

Under the Clean Fuel Research Initiative (CFRI), the Department of Science and Technology (DST) has launched various programmes. One of the programmes is for biomass, biofuel, and biogas. The objective of the programme is to develop ways to produce at scale, widely affordable, advanced biofuels for transportation and industrial applications. It resolves to continue working on the development and commercialization of novel sustainable bio-based fuels and products by encouraging early-stage technologies and nurturing cross-innovations with the objective of ensuring speedy commercialisation. [24]

Indian Agricultural Research Institute's (IARI) recent research in biomass, algal fuels and microbial biofuels, fermentation suggests active involvement in bioenergy and related research. Some of the projects are:

- Agri-residue and biomass management: Inhouse Project
- Production and processing of micro-algal biomass for biodiesel and other industrially important co-products: An algal refinery approach- National Agricultural Science Fund (NASF projects)
- Synthetic biology and metabolic engineering opportunities for enhanced production of biofuels through microbes- ICAR funded
- Evaluation of Jute and Mesta biomass for bioethanol production potential- ICAR Funded
- Production and Valorisation of Muconic Acid from Agricultural Waste to produce Adipic Acid combined fermentation and chemical catalytic process- ICAR Funded

Some of the funded projects by Indian Council of Agricultural Research (ICAR) are:

- Paddy straw residues management through in-situ and ex-situ microbial decomposition and mechanical interventions
- Production and Processing of Microalgal Biomass for Biodiesel and Other Industrially Important Co-products: An Algal Refinery Approach
- Sustainable Biomass Alternatives to Fossil-Fuel based Urea-Generation of Hydrogen Feedstock from Agro Residue and Biomass [30]

Few of the completed/ ongoing projects undertaken by Council of Scientific and Industrial Research (CSIR) are:

- A consolidated biomass process for integrated production of multiple products from fresh marine macroalgae
- Setting up 1 TPD pilot plant for converting waste plastics to diesel
- Technology demonstration and process flexibility for production of Bio-Aviation fuels
- Demonstration and Process Validation of Laboratory scale Vacuum Swing Adsorption (VSA) Process for Biogas Up-gradation to Pipeline Quality Fuel from Raw Biogas
- In-situ bioremediation technology
- Development of process for large scale production of β-glucosidase (BGL) enzyme for blending in biomass hydrolyzing cocktails to be used in Lignocellulosic Biorefineries
- Utilization of industrial waste through appropriate technologies for developing value-added Products
- Aircraft testing with Bio-Aviation fuel blended in Jet-A1 fuel
- Bio-methanation of coal rejects- low grade coal and biomass- Demonstration Model at village Gaurigram, Chandankiyari, Dhanbad
- Generation of energy from microalgal feedstock through CO2 capture from flue gasses

- Catalytic conversion of linear alkylbenzene raffinate to be utilized for Jet rocket fuel [31]

Appendix B: Bioenergy Research Landscape in the UK

B.1 Primary Research Funders

The primary research funders in the UK are the 7 research councils that together form UK Research and Innovation (UKRI). Those most relevant to bioenergy are the Biotechnology and Biological Sciences Research Council (BBSRC), the Engineering and Physical Sciences Research Council (EPSRC) and the Natural Environment Research Council (NERC), although the Economic and Social Research Council (ESRC) has historically supported some agricultural innovation focused research.

In principle EPSRC supports thermochemical technologies including combustion, gasification, pyrolysis, catalysis, hydrothermal processing etc as well as fuel and engine related work. BBSRC supports work on establishment, growth and harvesting of feedstock as well as biologically focused conversion technologies including fermentation and digestion. There is also significant focus on synthetic biology, genetic engineering, and other advanced activities.

NERC supports work on climate change, greenhouse gas removals, soil and earth ecosystems, biodiversity, carbon stocks etc. All of these are themes that may be applied to bioenergy, though there are not specific "bioenergy" programmes run by the council.

B.2 Main Research Programmes

EPSRC leads the energy programme on behalf of all research councils and has the largest programme of energy focused work of any council. A significant part of the managed programmes are the Supergen hubs. The most relevant of these to bioenergy is the Supergen Bioenergy Hub, which is funded jointly by EPSRC and BBSRC. The hub brings together academic, industrial and policy communities to focus on sustainable bioenergy development. Its scope encompasses: biomass resources; pre-treatment and conversion technologies (including thermochemical, biological and catalytic pathways); vectors (focusing on the tangible, useful intermediates to which biomass is converted in order to displace an existing fossil fuel use, such as heat, electricity, aviation fuel, substitute natural gas, polymers and functional materials) and systems (incorporating the sustainability assessment of all elements of the bioenergy system i.e. including environmental, economic and social evaluation).

BBSRC leads on biological conversion, biological processes and industrial biotechnology, which obviously relates closely to bioenergy systems. There are therefore several individual research projects (mentioned throughout this report), which are funded directly via their open research programme. They also support a set of networks in industrial biotechnology; some of which are very relevant to this work. They include the Biomass and Biorefinery network as well as a network focused on algae, one of high value products and one on fermentation. For postgraduate research the most relevant Centre for Doctoral Training is at the University of Leeds.

NERC focus more on the environmental impacts of bioenergy, including land and water so are particularly relevant for biomass production including algae. They have funded work particularly on biomass to energy with carbon capture and storage (BECCS) in the past and currently support the UK Energy Research Centre (UKERC), which carries out high level analysis of energy systems, including the potential and role of bioenergy. UKERC also has active interests in BECCS. BECCS is, of course, one of the greenhouse gas removal technologies that could be developed in future and there are several other similar nature-based solutions. These are being researched as part of an overarching programme on greenhouse gas removals that brings together a BECCS hub, one on afforestation, one on peatland restoration and one on biochar. Many aspects of the research in this programme are potentially relevant to bioenergy collaboration with India.

B.3 Key Research Institutes

There are at least 50 different academic institutes in the UK with active UKRI research projects on bioenergy. In addition, there are many that work directly with industrialists or have programmes for PhD research that incorporate bioenergy. It is therefore practically impossible to distinguish “key” research institutes. However, when progressing this report open calls for participation were issued to a variety of researchers related to and via the framework programmes described above. Therefore, by a process of self-selection it is reasonable to infer that all the authors of this report are based at research institutes that are active in bioenergy and that these are therefore effectively the key research institutes. Strategically it could be argued that the institutes where major programmes are based are key in the research framework and these include Aberdeen University, University of Aberystwyth, Aston University, Centre for Ecology and Hydrology, Imperial College, University of Manchester, Nottingham University, University of York.

B.4 Industrially Focused Research

As decarbonisation and net zero are currently key government priorities there is significant innovation support available for decarbonisation in the U.K. This is administered via 3 main agencies. Innovate UK is part of UKRI and has responsibility for supporting (including funding) research and innovation in the U.K. It provides funding for a range of size of companies for work that is commercializing (typically TL3-7). The support can range from smart grants that fund small levels of cost for company investigation of promising concepts through to more substantial support programmes that may form part of strategic initiatives over multiple years. Companies are usually expected to make some form of contribution but can receive support for their own costs via Innovate UK grant awards.

The Knowledge Transfer Network exists to support businesses in securing the knowledge and innovation know-how they need to progress innovative ideas through to commercial reality. It organizes events, information sessions and produces briefing and other material to support businesses in the commercialization of clean technologies.

Government departments (including Business Energy and Industrial Strategy (BEIS) and Department for Transport (DfT) provide significant support for a range of technology development under strategic initiatives. For example in the last 12 months the Net Zero Innovation Portfolio has had open compeitions for funding on biomass feedstock innovation, gasification and hydrogen with BECCS. The department for Transport runs regular TRIG innovation competitions for small grant awards in the transport sector.

B.5 International Research Funding Mechanisms

Programmes that provide direct funding for research (beyond costs for travel and networking) are more limited. To date the Newton programme has been a key instrument, but funding levels vary in level and geographic participants each year. Other resources such as the Energy Catalyst programme have seen immense success in some areas and the KTN programme has been rolled out in Africa. A generic issue is the lack of a single source of information for all international research collaboration funding opportunities and sometimes a lack of continuity in programmes or initiatives.

Appendix C: Indian Policy Support Mechanisms

Biogas Thermal/Off-Grid Programme-MNRE

Central financial assistance for the biogas thermal/off-grid programme is:

S No.	Capacity Range (kW)	Power Generation ('/kW)	Thermal Application ('/kW)
1	3-20	40,000/-	20,000/-
2	20-100	35,000/-	17,500/-
3	100-250	30,000/-	15,000/-

The total budget for each financial year between 2017-2020 is as follows:

S No.	Financial Year	Total Budget outlay in INR (in crores)
1	2017-18	5.50
2	2018-19	13.00
3	2019-20	16.30
	Total	**34.80**

Energy from Urban, Industrial and Agricultural Waste/Residue-MNRE

The total budget for the programme was INR 78.0 crores for Financial Years between 2017-2020. [41] Under this scheme, several Waste to Energy plants have been set up across the country. [42]

The central government has outlined the type of wastes and what constitutes under each type along with the criteria of technologies and capacity used for the projects. The criteria for technologies are:

- Projects based on waste-to-energy conversion technologies, namely, biomethanation, combustion, gasification, pyrolysis, or a combination thereof
- Projects for generation of power from biogas will be based either on 100% biogas engines or steam turbines with a minimum steam pressure of 42 bar
- The projects based on biomethanation of MSW should be taken up only on segregated/uniform Waste unless it is demonstrated that in Indian conditions, the waste segregation plant/process can separate waste suitable for Biomethanation
- Bio-CNG to be produced will have to meet the BIS specifications as per IS 16087: 2013

The Central financial assistance is based on the project type and the criteria given;

S No.	Wastes/ Process/ Technologies	Capital Subsidy
1	Power generation from Biogas, Solid, Industrial, Agricultural waste/residues excluding bagasse through Boiler + Steam Turbine Configuration	Rs. 2.00 crore/MW or Bio-CNG from 12000 m^3 biogas/day (Max. Rs. 5 crore/project)
2	Biogas generation from Urban, Industrial and Agricultural Wastes/residues	Rs. 0.50 crore/MW_{eq}. (12000 m^3 biogas/day with maximum Rs. 5 crore/project)
3	Power generation from Biogas (engine/gas turbine route) & production of bio-CNG for filling into gas cylinders	Rs. 1.00 crore/MW or bio-CNG from 12000 m^3 biogas (Max. Rs. 5 crore/project)
4	Power generation from Biogas, Solid, Industrial, Agricultural waste/residues excluding bagasse through Boiler + Steam Turbine Configuration	Rs. 0.20 crore/MW (Max. Rs. 1 crore/project

National Policy on Biofuel 2018

The central government launched Biofuel National Policy in 2018 which to chart the way forward to meet the Government's announcements in the energy domain such as electrification of all census villages by 2019, 24x7 electricity & 175 GW of renewable energy capacity by 2022, reduction in energy emissions intensity by 33%-35% by 2030 and share of non-fossil fuel-based capacity in the electricity mix is aimed at above 40% by 2030. An indicative target of 20% blending of ethanol in petrol and 5% blending of biodiesel in diesel is proposed by 2030. The steps are:

- Reinforcing ongoing ethanol/biodiesel supplies through increasing domestic production
- Setting up Second Generation (2G) bio refineries
- Development of new feedstock for biofuels
- Development of new technologies for conversion to biofuels.
- Creating a suitable environment for biofuels and its integration with the main fuels.

Biomass Based Cogeneration in Sugar Mills and other Industries in the Country-MNRE

The scheme was introduced for the years 2018-2021. The objective of the scheme was to support Biomass based Cogeneration Projects in Sugar mills and Other Industries for power generation in the country. Municipal Solid Waste was not covered under the programme with a budget of INR 170 Crores. Registered Companies, Partnership Firms, Proprietorship Firms, Cooperatives, Public Sector Companies, Government owned Firms could avail financial support available under the scheme. Central Financial Assistance (CFA) was defined to be provided at the rate of Rs.25 Lakh/MW (for bagasse cogeneration projects) and Rs.50 Lakh/MW (Non-bagasse Cogeneration projects) under the scheme. CFA was calculated on surplus exportable power as mentioned in Power Purchase Agreement (PPA) / Appraisal Report in case of bagasse cogeneration projects and on installed capacity in case of non-bagasse Cogeneration Projects. State Nodal Agencies (SNAs) were provided Rs. 1 Lakh/MW (Maximum Rs.10 Lakh per project) as incentive or service charge towards post installation monitoring of the projects and sending periodic reports to the Ministry. [44]

New National Biogas and Organic Manure Programme(NNBOMP)-MNRE

Salient Features of the programme:

- Allocation of Annual Targets by the MNRE to all State Implementing Agencies under NNBOMP with the starting of the Financial Year.
- Provision of 50% advance release of funds for annual allocated targets to the designated SND, PIAs i.e. State Rural Development Departments/ State Nodal Agencies and KVIC, Mumbai for Biogas plants.
- Special rates of CFA for NER States, SC and ST Categories for Biogas Plants.
- Provision of an additional Subsidy for cattle-dung-based biogas plants if linked with sanitary toilets, only for individual households (Rs. 1600/- Per Biogas Plant).
- Additional CFA for purchasing of 100% biogas engines and transportation of biogas from the site of the biogas plant to the site of biogas engine also incentivised.
- Across the country 8 number of Biogas Development and Training Centres (BDTCs) are providing technical and training, Field Inspections, and information & publicity assistance to the State Rural Development Departments/ State Nodal Agencies for biogas Development and awareness.
- Different types of Biogas Plant Models available such as (i) Deenbandhu fixed dome model (ii) KVIC's Floating Dome Design; and (iii) Prefabricated Reinforced Cement Concrete (RCC) digester with KVIC floating drum
- Provisions of 100% Physical Verification and Sample Village-wise biogas plant Monitoring mechanism.

- For Motivation and appreciation by MNRE to SRDDs & State Office of KVIC for overall performance and achieving highest annual targets allocated under the Scheme. [44]

Central Finance Assistance (CFA) was laid out for the FY 2017-18, 2018-19 and 2019-20 for biogas plant size from 1 m^3 to 25 m^3 with details about the process and prerequisites to avail the benefits of the scheme. [45]

Sustainable Alternative Towards Affordable Transportation-MoPNG

The scheme envisages to target production of 15 MMT (million tons) of CBG by 2023, from 5000 Plants. SATAT on compressed Biogas (CBG) encourages entrepreneurs to set up CBG plants, produce and supply CBG to Oil Marketing Companies (OMC) for sale as automotive and industrial fuels. Various Indian companies like Indian Oil, Bharat Petroleum, Hindustan Petroleum, Gail (India) Limited and Indraprastha Gas Limited have started projects under the scheme. Under the scheme, 3158 Letter of Intents have been issued, 15 plants have been commissioned and 4597 tonnes of CBG have been sold. [46] Under SATAT, various CFAs have been outlined by the Ministry of New and Renewable Energy (MNRE).

Not only MNRE or MoPNG, but other government ministries and departments, have taken initiatives to facilitate successful implementation of all the government policies. Some of these are

- State Governments
- State Government Departments (Renewable Power/Energy/Non-Conventional Energy/ additional sources of Energy/Science and Technology etc.)
- State Nodal Departments/Agencies
- State Electricity Boards/Transco/Gencos etc.
- Financial Institutions/Public Sector Banks
- State Rural Development Departments
- Khadi and Village Industries Commission
- All Biogas Development and Training Centres
- Indian Renewable Energy Development Agency (IREA)
- National Bank for Agriculture and Rural Development
- Department of Biotechnology
- Department of Science and Technology
- Ministry of Rural Development
- Ministry of Agriculture and more

Appendix D: UK Policy Support Mechanisms

Historically bioenergy and bioproduct production in the U.K. has been supported by a range of different energy policy mechanisms intended to generally support all renewable energy technologies in line with climate change commitments.

These include the Renewables Obligation which is a green certificate scheme for electricity from renewables. Bioenergy has qualified under various sub-categories corresponding to different levels of financial reward for schemes with energy crops, with combined heat and power capacity, using advanced conversion technologies etc. In general, a premium price is guaranteed for a fixed reward period provided certain sustainability thresholds are met. For very small suppliers, direct feed-in prices have historically been made available for renewable electricity generation, although self-supply is often the most economic option for many electricity generators and users.

The next longest standing mechanism is the renewable transport fuel obligation. This similarly works on a supplier obligation that results in “buyout” credits being recirculated as a premium price to those who deliver renewable fuel targets. There are minimum standards to be met in terms of sustainability and carbon savings, which gradually increase over time to maximize carbon savings and ensure continuous improvement. As with the renewables obligation specific adjustments can be made to support advanced fuels, which then qualify for multiple certificates etc.

Finally, a similar renewable heat scheme applies to heat that can be delivered directly or via injection into the existing natural gas grid. Injection into the gas grid requires standards be met in terms of methane specification and fuel quality, which some upgrading technologies may struggle to consistently achieve. Hence biomass/bioenergy schemes often directly supply heat to industrial users, avoiding stringent gas quality requirements.

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