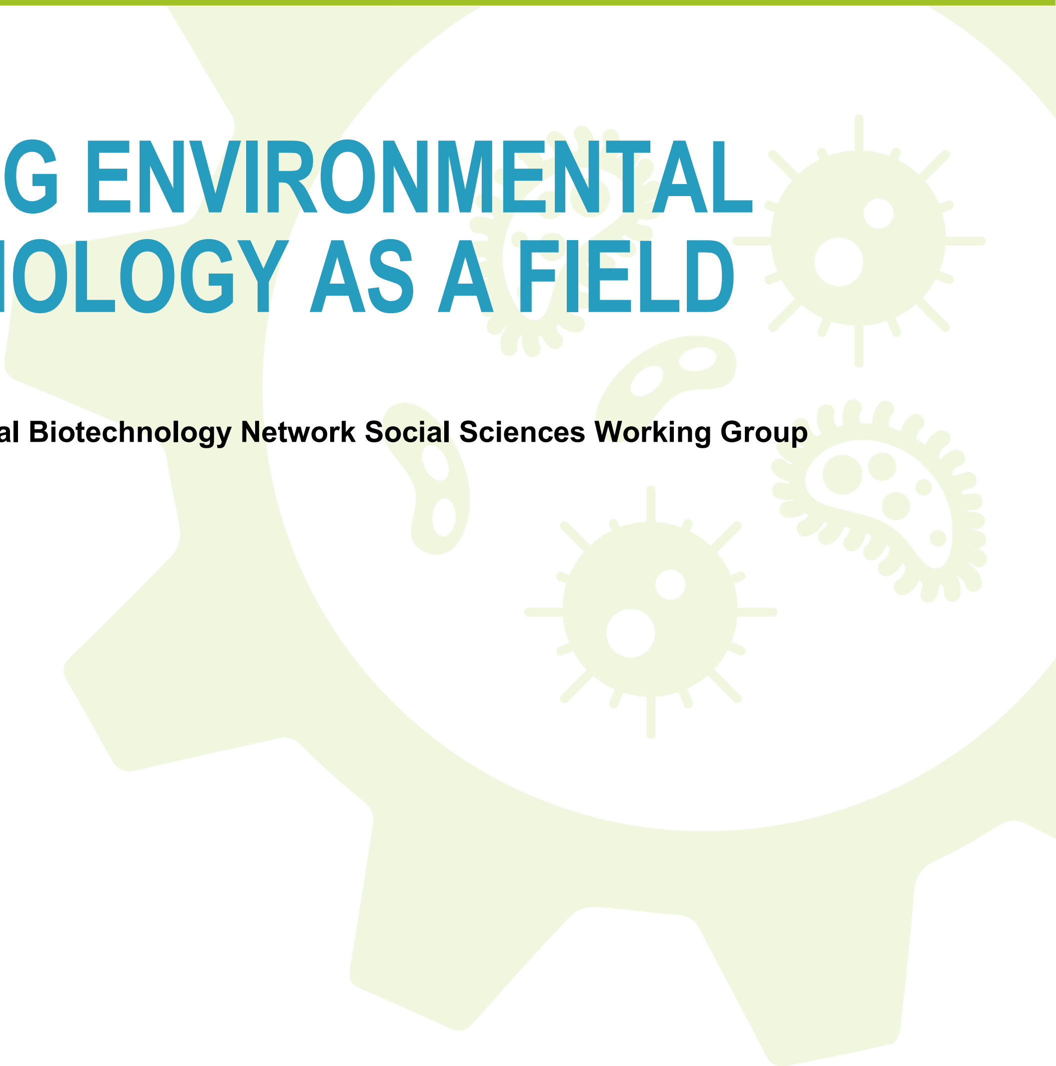
EXPLORING ENVIRONMENTAL BIOTECHNOLOGY AS A FIELD



A project of the Environmental Biotechnology Network Social Sciences Working Group

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Exploring Environmental Biotechnology as a Field

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Executive Summary

This small study set out to explore the past, present and future of environmental biotechnology as a field. Drawing on documentary evidence, bibliometric analysis and 12 interviews, it provides an initial mapping of definitions and clusters within the field, and presents tentative conclusions regarding its future directions, following discussions at an EBNet workshop convened on 4th November, 2024.

The study did not identify a single universally recognised definition of "environmental biotechnology", but that the ways different groups define the field diverge across various dimensions (types of organisms, methods applied, areas of application, and focus on prevention or mitigation).

The bibliometric study drew upon a corpus that went beyond using the single search term "environmental biotechnology" by developing a group of terms corpus that were more representative of the scientific field. The corpus was crafted to include topics related to search terms provided by an initial round of consultations and drew from publications in the last 50 years (1973-2022). The analysis shows that:

- Environmental biotechnology is a growing field, relative to the whole of science (Figure 5).
- Five different clusters are identifiable from the bibliometric mapping (see Figure 10), loosely characterised as: General Bioremediation; Contaminants & Phytoremediation; Biochar; Anaerobic Digestion and Nitrogen & Phosphorous Waste.
- As the field has developed over the last fifty years, more publishing activity has taken place in the biochar and anaerobic digestion fields (Figure 12), with biochar, biochar-anaerobic digestion and electron transport chain work in particular taking place in the most recent decade.
- Patterns of publishing activity across the world are severely skewed (Figure 14). Different countries show specialisation in different clusters (Figure 15), and also differences in their levels of international collaboration (as indicated by co-authorship) (Table 10).
- The contribution of India and China has increased dramatically in the last two decades, and China now publishes by far the greatest number of papers of any individual country (in our corpus).
- The term "environmental biotechnology" was used by a surprisingly small proportion of the papers in the corpus (881/200,963). This compares with 89 papers that used the term "industrial biotechnology", 275 that used "environmental engineering", 89 that used "synthetic biology" and 2 that used the more recent term "engineering biology" (Table 7).

Current dynamics show that more traditional approaches to environmental biotechnology (e.g. microbial ecology) are merging with different engineering disciplines as well as artificial intelligence and synthetic biology. The field is therefore evolving in ways that present opportunities for current application areas (e.g. wastewater management) focussing at localised scales, but also potentially extending to more large-scale/ global challenges (e.g. circular economy, climate change). Further work is required to explore these potential use cases and their social and environmental implications, to support associated policy-making across a range of areas.

1. Introduction

Despite being a diverse, interdisciplinary and important field, environmental biotechnology is under-studied from a social science perspective. This report, produced by the task-specific EBNet “Environmental Biotechnology and Social Sciences” Working Group, (EBSS WG) begins to fill that gap. It represents an initial exploratory study of the histories, contemporary dynamics and potential futures of the field, drawing on qualitative and quantitative social science methods.

The social sciences, in particular science and technology studies (STS), offer a range of conceptual and methodological resources for such an exploration. Scientific fields (Whitley 2000), also sometimes labelled as “specialisms” (Becher and Trowler 2001) emerge and evolve over time, and help build scientific communities and identities (Kastenhofer and Molyneux-Hodgson 2021). A scientific field such as environmental biotechnology entails a “common focus” and “accumulated knowledge shared by researchers”, but there may also be considerable disagreements within a field, as long as there is some agreement about how to resolve them (Fagerberg et al 2012). Scientific fields require shared infrastructure, such as “conferences and journals, agreed standards (for what is good work and what is not) and a merit-based reward system (that promotes the good work)” (Fagerberg et al 2012; Whitley 2000). The development of scientific fields involves differentiation, legitimation and resource mobilisation (Hambrick and Chen 2008), as well as the requisite level of ‘stickiness’ (Molyneux-Hodgson and Meyer 2009) to bind the community together. According to these definitions, “environmental biotechnology” can thus be viewed as a scientific field, amenable to examination via various methods commonly applied in STS.

The project “Exploring Environmental Biotechnology as a Field” used a bibliometric mapping of existing clusters, including interactions and overlaps between researchers involved in environmental biotechnology and other fields (Section 4). This quantitative analysis was complemented by qualitative, documentary analysis and 12 interviews which aimed to explore the ways in which different problem spaces, techno-scientific paradigms and innovation pathways have developed in environmental biotechnology and neighbouring fields since its emergence. Preliminary insights from the project (drafts of sections 1-5 of this report) were presented and discussed at a workshop organised by EBNet in November 2024 (see Appendix 2). The event engaged multiple stakeholder communities (on the basis of targeted and open invitations) to debate potential futures of environmental biotechnology as a field (with some discussions summarised in Appendix 3). These insights and further research led to the section on Futures of Environmental Biotechnology (Section 6). The report ends (Section 7) with a reflection on the limitations of the current study and suggestions for future research in this area.

2. Exploring the Past and Present of Environmental Biotechnology

The History of Environmental Biotechnology

Historians have provided detailed examinations of the emergence of biotechnology as “the engineering of nature” (Bud 1994) and accounts of early environmental applications of genetics (Krimsky 1991). For the purposes of this study, it is worth noting that biotechnology has historically made use of living things in the environment (knowingly or unknowingly) - with the domestication of plants, animals or microbes such as yeasts. As such, it could be said that all “biotechnology” - which has a history stretching back thousands of years (see Box 1) - has been related to “the environment”. However, more recently (since the 1980s) the term “environmental biotechnology” has emerged to describe a more limited set of activities (see Figure 1). This project sought to investigate the usage of the term and the state of the literature within (an internally consistent definition of) environmental biotechnology. Beyond the bibliometric study (outlined below), we drew on documentary evidence and semi-structured interviews with 12 scientists and practitioners across the UK “environmental biotechnology” community (both within and beyond EBNet).

Box 1: A Proposed Approach to Understanding “Generations” of Environmental Biotechnology as Applied to Water Treatment

The use of microbial processes in food is thousands of years old. Brewing dates back to ancient Egyptian and Sumerian civilisations, and the Babylonians are known to have brewed beers around 3000 BC (Bamforth 2023). “Domestication” of micro-organisms for (waste)water treatment emerged in stages alongside the history of urbanisation. Stormwater drain systems carried waste from some households in the Mesopotamian empire (3500 to 2500 BC) (Cooper 2005), and Babylonian latrines in the Akkadian period (2334–2154 BC) were connected to cesspools and (in the Northern Palace of Tell Asmar) sewers (George 2015). Boiling and filtering were used in ancient Greece and the ancient Egyptians are thought to have used alum as a coagulant (Hall and Dietrich 2000). However, whilst basic manipulation of micro-organisms played a role in these cases, knowledge and understanding of their importance (or even existence) was absent. This characteristic can be understood as defining the first generation of environmental biotechnology*. Miasma theory (the belief that contagious illness was spread through bad air) informed much of environmental biotechnology until the late 1800s (after Joseph Bazalgette was commissioned by the UK Parliament to build London’s sewer system in response to the “Great Stink” of 1858). Long after the invention of the microscope by Antoni van Leeuwenhoek (1632-1723, the “father of microbiology”), when John Snow, Robert Koch, Louis Pasteur and others pioneered the germ theory of disease and - alongside it - a greater understanding of the role of waste-borne micro-organisms in public health, environmental biotechnology began to manipulate microbes in a more informed way. Sewage systems and filtration, which saw significant innovation in Victorian Britain, combined with Ardern and Lockett’s activated sludge process to cultivate particular microorganisms in the early 20th Century and enabled wastewater treatment plants to respond to higher biological oxygen demand (BOD) levels and ammonia concentrations which were a product of urbanisation (2nd generation). The third generation of environmental biotechnology as applied in wastewater treatment might be thought of as emerging from the development of PCR as a means to monitor the presence/ populations of different species of micro-organisms and to manipulate conditions to affect these populations at the community level. Other monitoring techniques have been developed for a broader range of pollutants (e.g. pharmaceutical residues). The fourth generation represents the manipulation of micro-organisms’ genomes, by a range of techniques. This set of potential developments are revisited at the end of this report in Sections 5 and 6.

*The generations in this box are tentatively proposed by the research team as a way of understanding past and potential future developments of the field. This approach draws upon but differs from the generations described by Sedlak (2014) and that put forward by one of our interviewees (16/9/2024).

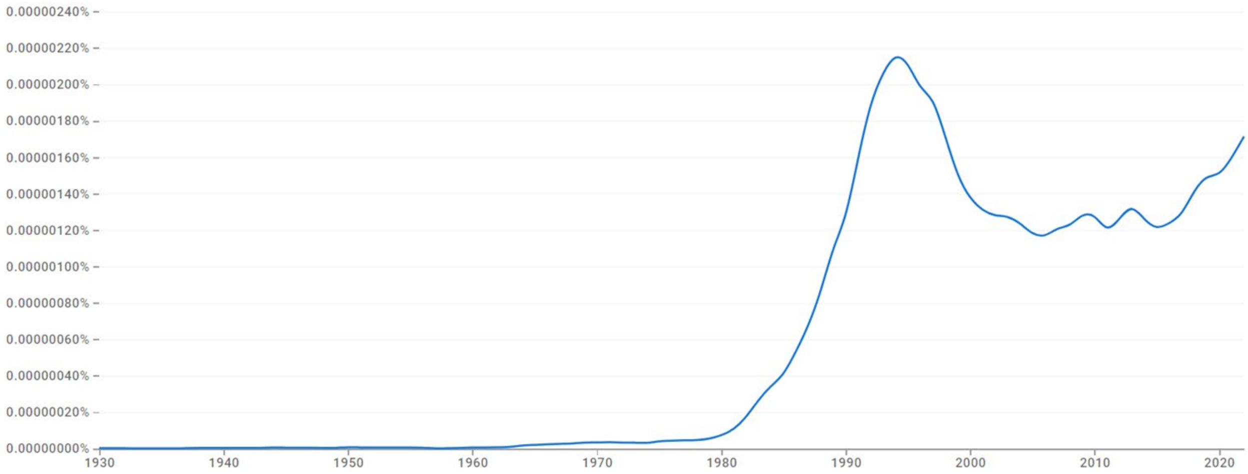

Figure 1. Google Ngram viewer “environmental biotechnology”, 1922-2022 - English corpus (accessed 9/10/2024)

Google Ngram viewer charts the use of a specific term in a corpus of books over selected years (Google 2024). The chart above shows that that the term “environmental biotechnology” was known from the 1960s onwards, but its use increased dramatically from around 1980. This coincided with the Diamond vs Chakrabarty case at the US Supreme Court, in which - for the first time in the US - a patent was awarded on a living organism, in this case a strain of *Pseudomonas putida* into which a genetic engineer working at General Electric (Ananda Mohan Chakrabarty) had transferred four different plasmids capable of breaking down constituents of crude oil (USPTO 1981). Beyond referring to applications of relevance to oil spills (incorporation of plasmids for camphor, octane, salicylate and naphthalene degradative pathways), Patent US4259444A reads “Conceivably plasmids may be discovered that will provide requisite enzyme series for the degradation of environmental pollutants such as insecticides, pesticides, plastics and other inert compounds.” The take-off in the use of “environmental biotechnology” coincided with the enactment by the US congress of the Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA) in 1980, that created the Hazardous Substance Response Trust Fund (Superfund). This invested US$1.6 billion over the following five years on cleaning up hazardous sites (EPA 2024), with significant expenditure on bioremediation (see for example EPA 2001).

After peaking in 1994 (0.0000022%), use of the term “environmental biotechnology” in the total English Google Ngram corpus declined, plateauing for the first twenty years of the century and beginning to rise again since 2017. It is not clear why this is the case, however it is intriguing that these patterns differ somewhat between the “British English” and “American English” corpera (see Figs 2 and 3 below).

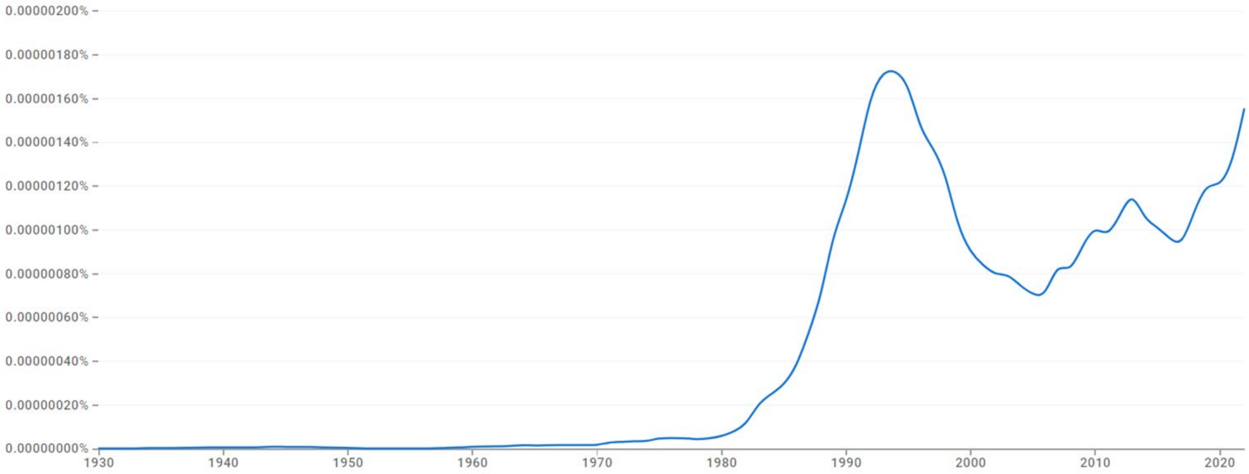

Figure 2. Google Ngram viewer “environmental biotechnology” - American English corpus, 1922-2022 (accessed 9/10/2024)

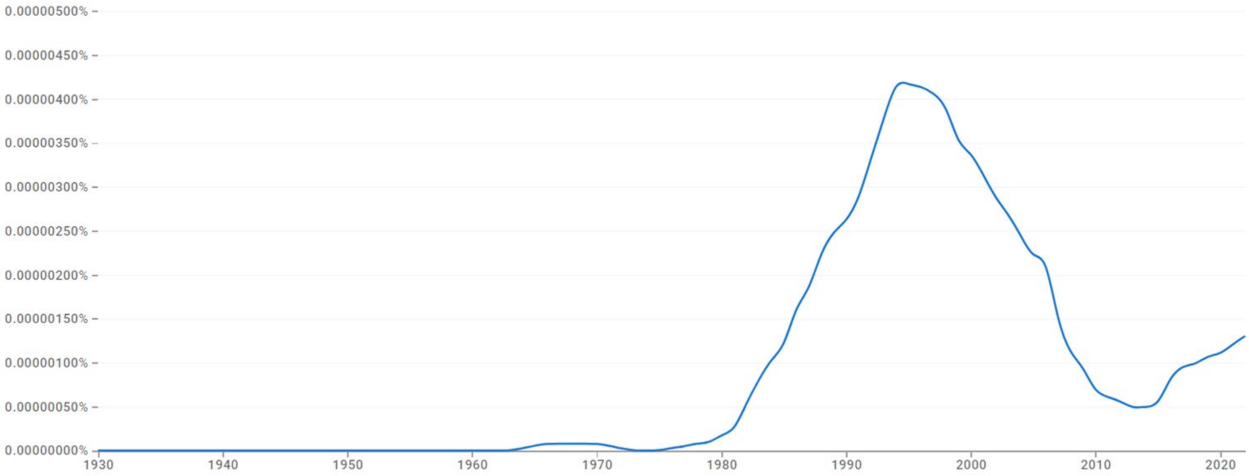

Figure 3. Google Ngram viewer “environmental biotechnology” - British English corpus, 1922-2022 (accessed 9/10/2024)

The drop in the use of the term “environmental biotechnology” in the British English corpus was more dramatic in the post 2000 period, and has not seen the same recovery as that in American English. A possible reason for this (which needs to be explored further) might be a reluctance to use the term since the (arguably more severe) public controversies around GMOs in the British media during the late 1990s (see for example Ely et al 2022). Alternatively, this pattern may relate to an increased adoption of American English standards in (scientific) venues in which the term “environmental biotechnology” is used, leading to a migration of British English writers to the American English corpus. Further research is needed to clarify this.

Regardless of the patterns of use of the term, it is clear from the nature of its use in different contexts that it is subject to multiple definitions. We next consider some of the evidence in this area.

3. Changing Definitions

The word “biotechnology” (“biotechnologie”) was first used by Karl Ereky in 1919 (Ereky 1919) in a book entitled “Biotechnology of meat, fat and milk production in large agricultural enterprises: written for scientifically educated farmers” (translation from original German). Since then, the scientific knowledge emerging from the field has received attention from governments wishing to support its application through policy. This has led to various definitions:

“The application of biological systems, organisms, and processes to manufacturing and service industries” (Spinks committee - UK government report on biotechnology, Spinks 1980).

“Any technique that uses living organisms (or parts of organisms) to make or modify products, to improve plants or animals, or to develop micro-organisms for specific uses” (US Office of Technology Assessment, OTA 1984)

“The application of science and technology to living organisms, as well as parts, products and models thereof, to alter living or non-living materials for the production of knowledge, goods and services.” (OECD 2013)

Turning to “environmental biotechnology”, the variety of definitions becomes much more expansive. Zylstra and Kukor (2005) adopted the approach of dividing and analysing the etymology of the various components of the term (environmental and biotechnology). Of the first, “environmental”, they include a range of meanings “from working directly in the environment to exploiting genes derived from the environment for various purposes”. With regard to “biotechnology”, they separately consider “bio” and “technology”. They argue that the prefix ‘bio’ sets disciplinary boundaries and “implies that the emphasis of this scientific discipline is on biology and biological processes, rather than on the chemical and physical processes that are components of the larger discipline of environmental science — with which environmental biotechnology has a natural affiliation”. They further argue:

> “With the suffix ‘technology’ attached, the sense of the prefix ‘bio’ is shifted in a subtle manner such that there is the implication of an applied or technical aspect to the work. This could be to apply newly developed technological tools (such as PCR) or information (such as genome sequences) to the analysis of biological processes in the environment. In this instance, environmental biotechnology would be the recipient of information from other scientific fields. On the other hand, the technological aspect could also be to exploit biological information gained from the environment by using it to understand environmental processes, such as carbon cycling and metal transformation. In a third technological sense, tangible biological materials as well as knowledge of biological processes in the environment could be transferred to other scientific fields. Excellent examples of this are biodiversity exploitation, industrial applications of biological processes, and pollution control and abatement.”

Zylstra and Kukor’s systematic parsing of these different elements and their inclusion of the exploitation of (genetic) information or processes in the environment mirrors a formal definition from the Australia and New Zealand Standard Research Classification (ANZSRC 2008), which includes “biodiscovery” and “biological control” (see Appendix 1).

EBNet uses the definition: “using engineered microbial systems for environmental protection, bioremediation and resource recovery” (EBNet 2024). This definition permits a lot of latitude, as “engineered systems” allows (but does not necessarily require) the inclusion of genetically modified organisms. It also presents obvious and deliberate restrictions - such as the exclusion of biotechnology involving plants (phytoremediation) or animals (zooremediation). Further, it emphasises the treatment of waste or pollution over the production of energy or biomaterials (as a substitute for more environmentally damaging approaches). Nevertheless, it conforms *broadly* with definitions offered by EBNet colleagues who, when questioned individually, suggested that environmental biotechnology can be defined as “the use of biologically-mediated systems for environmental protection and bioremediation”, with the added comment that “it can include resource recovery when this forms an integral part of such systems”, emphasised “the use of microbes to clean, valorize or recycle a waste to protect the environment”, and in addition offered up biosurfactants as “chemicals that can enhance bioremediation and [are] useful in a range of biotech processes.”

Another broad definition - albeit retaining the focus on microbes - is put forward by Rittman (2006), who suggests that environmental biotechnology can be defined as “managing microbial communities to provide services to society” (in which the public good aspect is implicit - “to society”). He goes on to argue that “microbial ecology and environmental biotechnology are inherently tied to each other. The concepts and tools of microbial ecology are the basis for managing processes in environmental biotechnology; and these processes provide interesting ecosystems to advance the concepts and tools of microbial ecology.” The tools of microbial ecology refer primarily to the manipulation of populations of different microorganisms, rather than the manipulation of those organisms at the genetic level, and thus relates to the 3rd generation of environmental biotechnology (see Box 1).

Others broaden the fields of application to “agriculture, resource conservation, environmental protection, monitoring of contaminated environment, and waste management” (Singh 2016), or cast it wider still: “environmental biotechnology includes the application of biotechnology processes and products to any aspect of the environment” (Fulekar 2010). Recent discussions fit with such definitions about the application of synthetic biology (or engineering biology, discussed later), comply with such definitions and are expanding the scope of environmental interventions. For example, the Environmental Biotechnology Innovation Centre (EBIC) states that “environmental biotechnology is the application of biotechnological processes to solve environmental problems” (EBIC 2024). The website further expands on this definition: “environmental biotechnology involves the use of microorganisms, plants, and their enzymes to treat contaminated environments, reduce pollution, and manage waste. Key applications include bioremediation (cleaning up contaminated soil and water), biofiltration (removing pollutants from air and water), and the development of sustainable biofuels and biodegradable materials. This field aims to harness biological systems to develop eco-friendly and efficient solutions for environmental sustainability.”

Professional societies possess their own definitions. The International Society for Environmental Biotechnology (founded in 1992) defines environmental biotechnology as "the development, use and regulation of biological systems for remediation of contaminated environments (land, air, water), and for environment-friendly processes (green manufacturing technologies and sustainable development)" (Nature Scientific Reports 2024). In some cases, it is possible to trace how definitions have developed over time. In 1999, the European Federation of Biotechnology (EFB) (inaugurated at the first European Congress of Biotechnology in Interlaken, Switzerland, in 1978) defined environmental biotechnology as “the integration of natural sciences and engineering in order to achieve the application of organisms, cells, parts thereof and molecular analogues for the protection and restoration of the quality of our environment” (EFB 1999, cited in Ezeonu et al 2012). The EFB Environmental Biotechnology Division currently breaks down the various applications: “Environmental Biotechnology provides effective tools, which are sustainable from economical, environmental and social points of view and can be applied to:

- Monitor and reduce the risk to humans from contaminated sites and from the storage of municipal and industrial (bio)wastes
- Clean up water, soil, and air to achieve good quality standards and reuse treated wastewater to reduce the demand of natural water for industrial, agricultural and municipal purposes
- Turn (bio)waste, including wastewater, into bio-based biodegradable/biocompatible and renewable chemicals for material and fuel production with a measurable reduction of i) Biowaste disposal-borne human risks, ii) Use of scarce fossil fuels or food crops-based biorefineries, and iii) Climate change impact related to CO2 production.

Environmental Biotechnology has a broad industrial application potential such as the sustainable remediation of sites and wastewaters and the innovative chemical and energetic valorization "biorefinery“ of (bio)wastes generated by various industrial sectors” (EFB 2024). The move towards addressing global environmental challenges as per EFB’s “iii) Climate change impact related to CO2 production” (as well as other global challenges such as plastic wastes, persistent pollutants or other planetary boundaries (Rockström et al 2009)) marks a shift away from the traditional domains of environmental biotechnology (1st, 2nd and 3rd generations), which have been local in nature.

Other contributions to the field use related terms such as “environmental engineering” (Vallero and Gunsch 2020), “industrial biotechnology” (Singh 2014) or even “ecobiotechnology” (Gula et al 2020); or discuss the application to environmental challenges of synthetic biology “the design and engineering of biologically based parts, novel devices and systems as well as the redesign of existing, natural biological systems.” (UKSBRCG 2012, p.4). In order to explore some of these further, we used bibliometric approaches (see below).

Our interviews also illustrated some differences in opinion around environmental biotechnology (with some interviewees even questioning whether they fell within that field.) Some of their work focussed on abatement of impact from waste (e.g. heavy metals, sewage, cleaning up the mess from industrial/ urban society), whilst a minority focussed on the utility of waste streams as an input to industrial processes (and process innovations to make these more efficient, contributing to circularity and mitigation of harm through substituting for damaging processes). The abatement/mitigation or treatment/prevention dimension is an important one, to which we return in Section 5. “Current dynamics and debates in environmental biotechnology”. The specific problem focus of interviewees (e.g. human waste, heavy metals, industrial waste from consumer products such as surfactants, PFAS, food waste from brewing and baking) led to different definitions and visions for environmental biotechnology innovation. Despite these differences, and the ambiguous attachment to the term “environmental biotechnology”, it still plays an important role. It is interpreted somewhat differently by various groups, but retains a common identity across them - and can be mobilised to delineate communities, advocate for resources or to negotiate legitimacy and authority. The ongoing metamorphosis of this community (and of the term) is discussed further in the next section, and revisited in Section 5 of this report.

4. Exploring the Bibliometric Landscape

Bibliometrics provides a range of tools and approaches that can help to identify, define and explore scientific fields through a range of different techniques (Glänzel et al 2019). This study undertook a bibliometric mapping of existing clusters within environmental biotechnology and explored interactions and overlaps between environmental biotechnology and other, related fields (industrial biotechnology, environmental engineering, synthetic biology, engineering biology). We explored organisational, geographic and cognitive clusters using established methods (Rotolo et al 2017; Martin et al 2012) and looked at trends in publications across countries, specialisms and interacting fields.

Methods

Bibliometric studies have used a number of approaches to attempt delineation of scientific fields. Small et al. (2014) used small clusters to identify emerging topics in science. Carley et al (2017) used publication data to investigate the disciplinary profiles of organisations, funding programmes and topics. Rotolo et al (2017) explored 3 emerging fields in terms of their geographical, social and cognitive space using publication and patent data. Martin et al (2012), for example, used cited papers in the established series of handbooks of Science and Technology Studies to explore the field.

This study wished to examine the field without limiting itself to those studies explicitly identifying themselves as “environmental biotechnology”. We also recognise that scientists - when communicating with each other through journal articles - rarely use the terms that describe their communities. On this basis we went beyond using the single search term “environmental biotechnology” to an approach involving developing a corpus that was more representative of the scientific field, whether or not this term appeared in the article. In order to fetch this bibliometric corpus, a complex search string involving different terms, compound terms (such as "anaerobic treatment" AND ("wastewater" OR "waste water")) and boolean operators was constructed. First, potential search terms were derived from five initial sources:

1) The project proposal produced for EBNet;
2) Terms taken from EBNet working groups (e.g. anaerobic digestion, anaerobic granulation, anaerobic fermentation, biochar[1]);
3) An initial list of environmental biotechnologies provided by the EBNet PI;
4) Responses to emails sent to PIs and Co-Is associated with EBNet and EBIC, asking for possible keywords for environmental biotechnology;
5) A group workshop session in May 2024.

These initial potential search terms were investigated to see if they could yield results related to environmental biotechnology in three rounds, in which the terms were increasingly qualified to construct compound terms where necessary. These test searches were performed starting from

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[1] Some areas of biochar research may have little or no relation to the field, but others (which appeared in our corpus) have applicability to waste valorisation or other aspects of environmental biotechnology.

19th June 2024 on the title/abstract[2] on the Dimensions database[3], a large-scale, global proprietary database of publications and other research data. Dimensions is more comprehensive than conventional databases like Web of Science or Scopus (Singh et al. 2021). We limited results to the “Article” publication type, with twenty publications per test being checked in the first and second rounds - rising to fifty for the third round.

In the first round of testing, if any additional potentially useful terms were found in reading an abstract, these terms were added to the list of terms to test. An example of a search term found in this way is “sequencing batch reactor”. During the first round of tests, some terms proved immediately unsuitable - usually due to returning too many results that were deemed off-topic with no obvious way to qualify the search terms. For instance, the compound term “detoxify AND (contamination OR contaminant OR water OR sludge OR sediment OR soil)” yielded 55% of results off-topic, despite the inclusion of many qualifying terms. Other search terms were deemed immediately suitable, yielding a high proportion of on-topic publications with either no qualification, or simple ad hoc qualifications. An example of this was the term “activated sludge”.

The second round of testing was intended for terms that fell between these extremes - where the search term yielded too many off-topic results, but where a more systematic attempt to qualify the results into a compound term was considered likely to produce better data. As such a list of supplementary terms, loosely clustering into terms that were biological/biotechnological (e.g. bacteria, biosensors) or environmental (e.g. food waste, contamination) in nature, were created. These were then combined with the search terms of ambiguous utility for a second round of testing, and a suitable compound term was generated for all of these.

A third and final round of testing, on a higher sample size of fifty publications per term, was then performed: firstly on a compound term generated from all suitable terms found in the first round of testing, strung together by “OR” operators; secondly on each compound term deemed suitable in the second round of testing, both individually and combined into a single compound term by “OR” operators; and finally on a complex search string[4] combining all terms and compound terms.

The only change made in this final round of cleaning the search string was not to include the specific term “synthetic biology”. This is a term that can overlap with environmental biotechnology, but is not a synonym, and we investigated how often this term organically arose in our corpus, alongside other terms such as “engineering biology” (a related term in more recent use) to explore overlapping fields.

The search terms (after the first round of testing) that were used without any further qualification are laid out in Table 1.

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[2] We did not search for documents with “environmental biotechnology” in all fields, but only in the title or abstract. This is a standard approach in bibliometrics because searching in all fields is likely to bring less relevant articles into the data set.

[3] With thanks to Dimensions for generously providing this project with free access to the data.

[4] The terminology of the final search term being referred to as a “search string” derives from Porter et al (2007).

Table 1. Summary of terms and compound terms identified in the first round of testing.

Description of term	**Search term/compound term**
activated sludge	(activated sludge)
anaerobic digestion	(anaerobic digestion)
anaerobic granulation	(anaerobic AND (granulation OR granule OR sludge))
biological phosphorous/nutrient removal	"biological phosphorous removal" OR (biological nutrient removal)
bioaugmentation	bioaugmentation
biological/trickling/percolating filters	("biological filters" OR "biological filtration" OR "biofiltration" OR "trickling filters" OR "percolating filters")
bioleaching	(bioleaching OR (leaching AND (bacteria OR bacterial OR fungi OR fungal OR microbe OR microbial OR algal OR algae OR microalgae OR microalgal)
biorecovery	biorecovery
bioremediation/phycoremedition/phytoremediation	((remediation OR remediate) AND (biotech OR biotechnology OR biotechnological))
	bioremediation OR bioremediate
	phytoremediation OR phycoremediation
biosequestration	biosequestration
biosorption	biosorption
composting	composting
constructed wetland	"constructed wetland"
environmental biotechnology	"environmental biotechnology"
sequencing batch reactor	(sequencing batch reactor)
slow sand filters	("slow sand filtration" OR "slow sand filter")
waste biorefineries	(waste biorefineries OR waste biorefinery)
waste stabilisation ponds	("Waste stabilisation pond" OR "waste stabilization pond")

Table 2 lists supplementary terms, loosely clustered into terms that were biological/biotechnological or environmental in nature, which were combined in the second round of testing in order to supplement the search terms above with compound terms. The search terms that required qualifications too complex to map in Table 2 are as follows:

- (bioleaching OR (leaching + algae/bacteria/fungi/microbes)) AND (contamination/pollution/recovery/slag/spent/tailings/waste)
- recovery AND (bacteria/microbes) AND (contamination/slag/spent/tailings/waste/wastewater) NOT (hospital/intensive care/medical)

Both of these represent cases where both biological/biotechnological and environmental terms were needed for sufficient qualification, and the second example also required an exclusion of terms related to a medical context.

The final search string used was: (bioremediation OR bioremediate OR biosequestration OR biorecovery OR (anaerobic digestion) OR (anaerobic AND (granulation OR granule OR sludge)) OR (waste biorefineries OR waste biorefinery) OR (activated sludge) OR "biological phosphorous removal" OR (biological nutrient removal) OR "constructed wetland" OR ("Waste stabilisation pond" OR "waste stabilization pond") OR composting OR bioaugmentation OR biosorption OR phytoremediation OR phycoremediation OR (sequencing batch reactor) OR (bioleaching OR (leaching AND (bacteria OR bacterial OR fungi OR fungal OR microbe OR microbial OR algal OR algae OR microalgae OR microalgal) AND (contaminated OR contaminant OR spent OR waste OR recovery OR slag OR tailings OR pollution OR pollutant)))) OR ("biological filters" OR "biological filtration" OR "biofiltration" OR "trickling filters" OR "percolating filters") OR ("slow sand filtration" OR "slow sand filter") OR ((remediation OR remediate) AND (biotech OR biotechnology OR biotechnological)) OR ("anaerobic treatment" AND ("wastewater" OR "waste water")) OR (("wastewater treatment" OR "waste water treatment") AND ("biological" OR biotech OR biotechnology OR biotechnological OR bacteria OR bacterial OR microbe OR microbial OR fungi OR fungal)) OR (((biological OR bacterial OR microbial OR fungal) AND "resource recovery")) OR ((biochar OR hydrochar) AND (environmental OR environment OR remediation OR remediate)) OR ((anaerobic fermentation) AND ("wastewater" OR "waste water" OR "solid waste" OR "food waste" OR "reactor" OR "bioreactor" OR "sludge")) OR ((anammox) AND ("wastewater" OR "waste water" OR "solid waste" OR "food waste" OR "reactor" OR "bioreactor" OR "sludge")) OR ("metal recovery" AND (biological OR bacteria OR bacterial OR microbe OR microbial OR fungi OR fungal OR plant OR algae OR algal OR microalgae OR microalgal)) OR ((("recovery" AND "bacterial") OR ("recovery" AND "microbial")) AND ("waste" OR "wastewater" OR "contaminated" OR "slag" OR "spent" OR "contaminant" OR "tailings") NOT "intensive care" NOT "hospital" NOT "medical") OR ((biodegradation) AND (valorization OR valorisation OR recovery OR remediate OR remediation)) OR ("carbon sequestration" AND (plant OR microbe OR microbial OR bacteria OR bacterial OR fungi OR fungal OR biological OR algae OR algal OR microalgae OR microalgal)) OR ((biohydrogen OR "bio hydrogen") AND (bacteria OR bacterial OR microbe OR microbial OR fungi OR fungal OR plant OR algae OR algal OR microalgae OR microalgal)) OR "environmental biotechnology" OR ((biosensors OR biosensing) AND (remediation OR remediate)) OR (biosurfactants AND (waste OR valorization OR valorisation OR "metal removal" OR "removal of heavy metals" OR "circular" OR "contamination" OR "contaminant" OR "removal"))

The corpus used in the bibliometric analysis was fetched from Dimensions on the 16th July 2024, consisting of document types “Research Article”, “Conference Paper”, “Review Article” and “Research Chapter”[5] dating from 1973-2022, by using our search string to search in the title or abstract of publications.

In the first stage of the bibliometric analysis, the corpus was analysed in terms of indicators such as publishing trends over time, notable fields of research, relationship to other related fields, prominent sources, high-profile research organisations and geographical spread of research.

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[5] We did not include editorials because they tend to be about research agenda setting, rather than being unique research contributions.

Table 2. Summary of compound search terms comprising a combination of an environmental and a biological term (X indicates where environmental and biology/ biotech terms were combined in the final search string e.g. “"anaerobic treatment" AND ("wastewater" OR "waste water")”.

	Environmental terms	(bio) reactor	carbon sequestration	circular (economy)	contamination	Environment (al)	(bio) hydrogen	metal recovery / removal	recovery / removal	remediation	sludge	valorisation	waste (food)	waste	waste (solid)	wastewater	wastewater treatment (+ resource recovery)
Biology/ biotech terms																	
anaerobic fermentation		X									X		X		X	X	
anaerobic treatment																X	
Anammox		X									X		X		X	X	
biochar / hydrochar						X				X							
Biodegradation									X	X		X					
biology / biotechnology (concept)										X							X
Biosensors										X							
Biosurfactants				X	X			X	X			X		X			
(micro)algae			X				X	X									
Bacteria			X				X	X									X
Fungi			X				X	X									X
microbes (general)			X				X	X									X
Plants			X				X	X									

To explore the corpus in more depth, the data were mapped to produce visualisations highlighting different features of the scientific landscape. Mapping was carried out using freely available software called VOSviewer, developed by researchers at the Centre for Science and Technology Studies (CWTS) at Leiden University (van Eck and Waltman 2010). VOSviewer uses the visualisation of similarities (VOS) mapping technique (van Eck and Waltman 2010). This mapping technique places nodes so that more similar nodes are found closer together and less similar nodes are further from each other. Many different types of data can be mapped in this way, such as terms found in the titles and abstracts of publications, fields of research, or citation relationships between publications.

In order to visualise where the field of environmental biotechnology is located with reference to the rest of science, a map of the whole of science was also constructed using all of the publications in the Dimensions database since 2000, following Waltman and van Eck (2012) (see "How does environmental biotechnology relate to the rest of science?") In this map, the nodes represent micro-level fields within science and their location in the map is based on direct citation relations of the papers in each micro-level field, so that fields that are more similar in terms of citation patterns are found nearer to each other and those that are less similar are found further away from each other. The publication data representing the field of environmental biotechnology was then overlaid (i.e. projected) onto the base map of the whole of science.

To visualise the internal structure of the field of environmental biotechnology and with higher resolution, another map was generated based on the bibliographic coupling relationships within our corpus, depicting links between publications that share common references.[6] Variants of this map were tested, as were the attraction/repulsion and the cluster resolution, and these settings were deemed to provide optimum delineation between clusters on the map, and maximum coherency of subject area within clusters. This map (discussed further in "What types of clusters can be found in the field of environmental biotechnology?") was also used as a base map upon which to overlay other data such as publication trends over time and across countries.

Findings

General statistics and publishing trends in environmental biotechnology

The search described above fetched a total of 200,963 publications, drawn from 12,745 sources (journals, edited books). These were made up of the following document types:
Research Article - 171,354
Review Article - 12,763
Research Chapter - 12,475
Conference Paper - 4,371
The field has shown significant growth over the past 50 years (Fig. 4). The average age of the documents fetched was just over 10 years.

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[6] Specifically, the map (see later Figure 10) shows the top 1000 publications by link strength according to similarity in citation patterns, limited to publications with at least 100 citations. The maps were produced in VOSviewer with settings of attraction = 2, repulsion = 1 (affecting layout) and cluster resolution = 0.7 (affecting characterisation of nodes into clusters).

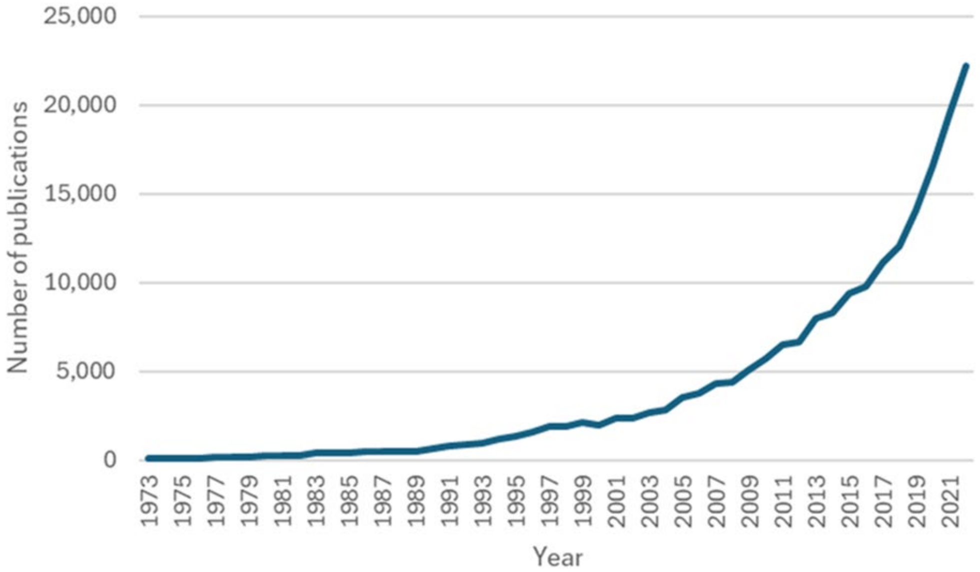

Figure 4. Number of publications in our environmental biotechnology corpus from each year (1973-2022)

This could be due to the dramatic increase in scientific publishing over the same period, but even when we control for that by plotting environmental biotechnology publications as a percentage of all science publications over the last 50 years, we still find an increase (Figure 5).

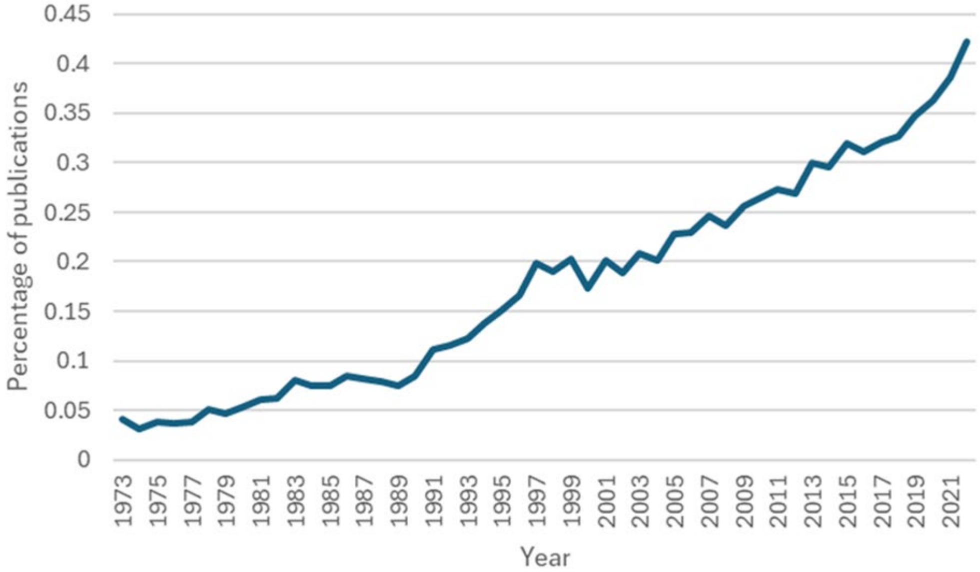

Figure 5. Environmental biotechnology publications per year as a percentage of publications in all of science (in the database Dimensions) for the last 50 years (1973-2022); on average overall environmental biotechnology publications make up 0.18% of all science, growing from approximately 0.05% in the 1970s to 0.42% in 2021.

How does environmental biotechnology relate to the rest of science?

The map in Figure 6 represents the whole of science, generated using all of the publications in the Dimensions database, based on direct citation relations between publications (Waltman and van Eck 2012). Each node represents a research topic or micro-field within science, and the colours indicate different large disciplinary areas of science: blue for physical sciences and engineering, purple for mathematics and computer science, red for social sciences and humanities, green for biomedical and health sciences and yellow for life and earth sciences.

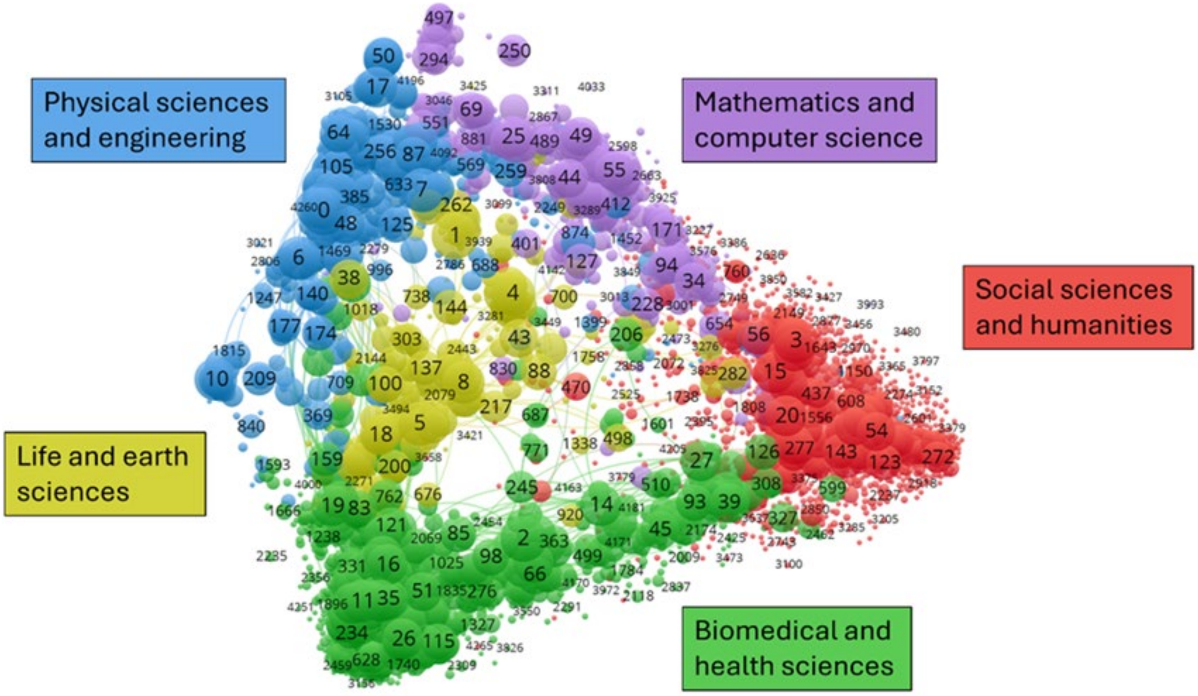

Figure 6. Global map of science using all publications in the Dimensions database, based on citation relations between publications.

If we overlay our environmental biotechnology corpus onto the base map as in Figure 7, we can see how it relates to the rest of science. The map above shows where the publications in our corpus are found according to the percentage of environmental biotechnology publications in each micro-level field node, from purple indicating no publications, to yellow indicating 30% environmental biotechnology publications. The map shows a high density in the life and earth sciences (yellow), but also some physical sciences and engineering (blue) and biomedical and health sciences (green) relationships. There are not many social science micro-level fields (red) which contain a high percentage of environmental biotechnology publications, but two examples of such fields are 3987, which is about wastewater treatment plants (4.37%), and 2072, which is about food waste behaviour (2.75%).

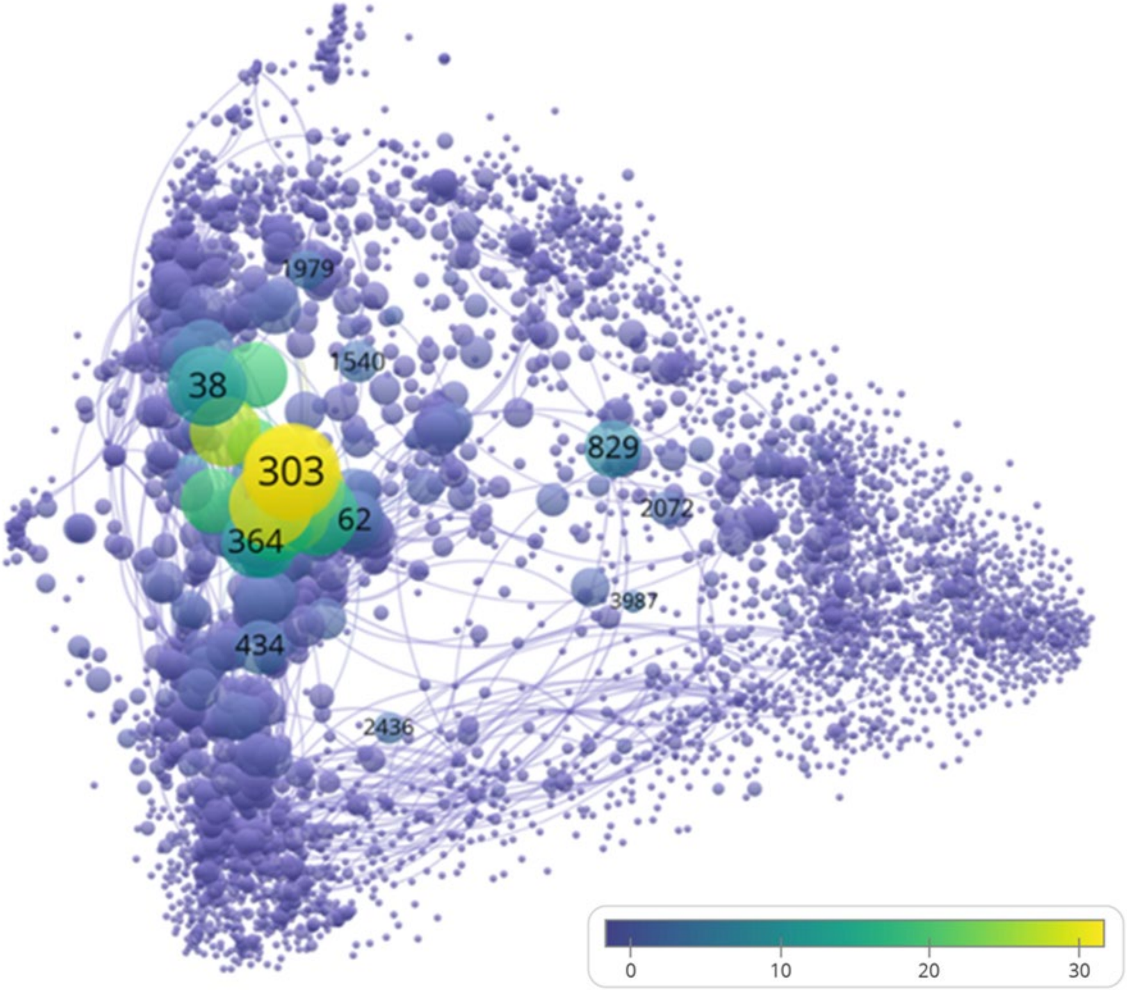

Figure 7. Overlay of environmental biotechnology corpus publications onto the global map of all of science according to the percentage of environmental biotechnology publications in each micro-level field node, from purple indicating no publications, to yellow indicating 30% environmental biotechnology publications.

Table 3 shows the IDs of the micro-level field nodes on the global map of science that are prominent in our corpus (as shown in Figure 7), the sources (journals) they are commonly found in and the concepts they signify. For example, micro-level field 303 contains over 50% publications related to environmental biotechnology, and its concepts include: biogas yield, methane potential, production of biogas, biogas production and co-digestion. Some of the main journals associated with micro-level field 303 are Bioresource Technology, International Journal of Hydrogen Energy, Water Research, Waste Management and Water Science & Technology. This micro-level field relates to life and earth sciences, and physical sciences and engineering.

To take another example, micro-level field 829 is also related to life and earth sciences, and physical sciences and engineering, and some of the main journals are Waste Management, Waste Management & Research: The Journal for a Sustainable Circular Economy, Journal of Cleaner Production, Resources Conservation and Recycling and Sustainability. Micro-level field

829 contains nearly 8% environmental biotechnology publications, and its concepts include: bioreactor landfills; municipal solid waste management; landfill gas; MSW (municipal solid waste); solid waste landfills.

With these two examples, we can begin to see the diversity of research on environmental biotechnology, and where it is located within a global map of science.

Table 3. Top 20 clusters from the CWTS map of science, by percentage of environmental biotechnology papers

Node	Description	No. pubs. env. bio.	% pubs. env. bio.
303	Main fields: Life and earth sciences; Physical sciences and engineering Sources: bioresource technology; international journal of hydrogen energy; water research; waste management; water science & technology Concepts: biogas yield; methane potential; production of biogas; biogas production; co-digestion	20,629	54.3
603	Main fields: Life and earth sciences; Physical sciences and engineering Sources: bioresource technology; water science & technology; water research; the science of the total environment; proceedings of the water environment federation Concepts: anammox activity; aerobic granules; anammox process; Brocadia; Kuenenia	13,622	52.4
1282	Main fields: Life and earth sciences; Physical sciences and engineering Sources: ecological engineering; water science & technology; the science of the total environment; environmental science and pollution research; water Concepts: subsurface flow; treatment wetlands; Everglades; vertical flow; wetland system	5,652	45.6
1306	Main fields: Life and earth sciences Sources: bioresource technology; acta horticulturae; waste management; journal of environmental management; compost science & utilization Concepts: composting process; thermophilic phase; food waste; compost quality; waste composting	4,978	41.5
448	Main fields: Life and earth sciences Sources: journal of hazardous materials; chemosphere; environmental science and technology; international biodeterioration & biodegradation; environmental science and pollution research Concepts: biosurfactant production; phytoremediation; bioaugmentation; total petroleum hydrocarbons; biostimulation	10,070	32.3
885	Main fields: Life and earth sciences Sources: the science of the total environment; chemosphere; bioresource technology; environmental science and pollution research; journal of hazardous materials Concepts: biochar amendment; effects of biochar; biochar application; application rates; pot experiment	5,504	29.8
1018	Main fields: Life and earth sciences; Physical sciences and engineering Sources: bioresource technology; international journal of hydrogen energy; journal of power sources; bioelectrochemistry; the science of the total environment Concepts: maximum power density; MFC; microbial fuel cells; internal resistance; MFC performance	4,213	25.9
1912	Main fields: Life and earth sciences; Physical sciences and engineering Sources: chemosphere; bioresource technology; the science of the total environment; journal of chemical technology & biotechnology; journal of hazardous materials Concepts: odorants; elimination capacity; methylsiloxanes; bed residence time; D5	1,068	19.0
1204	Main fields: Life and earth sciences; Physical sciences and engineering Sources: bioresource technology; international biodeterioration & biodegradation; journal of hazardous materials; chemosphere; applied microbiology and biotechnology Concepts: azo dyes; textile effluent; textile dyes; textile wastewater; dye concentration	2,538	18.9
996	Main fields: Physical sciences and engineering; Life and earth sciences Sources: hydrometallurgy; minerals engineering; minerals; mine water and the environment; applied geochemistry Concepts: bioleaching process; A. ferrooxidans; chalcopyrite; Acidithiobacillus ferrooxidans; heap leaching	3,066	18.6

Table 3 ctd. Top 20 clusters from the CWTS map of science, by percentage of environmental biotechnology papers

D	**Description**	**Cluster**	**No. pubs. env. bio.**	**% pubs. env. bio.**
451	Main fields: Life and earth sciences; Physical sciences and engineering Sources: the science of the total environment; chemosphere; environmental science and pollution research; water research; journal of hazardous materials Concepts: antibiotic resistance genes; tetracycline; resistome; antibiotic concentrations; fluoroquinolones	4	5,408	17.4
137	Main fields: Life and earth sciences Sources: environmental science and pollution research; chemosphere; the science of the total environment; ecotoxicology and environmental safety; journal of hazardous materials Concepts: Cd stress; Cd treatment; Cd tolerance; Cd toxicity; Cd uptake	4	8,621	17.1
1343	Main fields: Life and earth sciences Sources: the science of the total environment; chemosphere; environmental science and pollution research; journal of environmental science and health part b; journal of agricultural and food chemistry Concepts: aminomethylphosphonic acid; determination of glyphosate; atrazine degradation; glyphosate; glyphosate concentrations	4	1,585	13.7
364	Main fields: Life and earth sciences Sources: bioresource technology; algal research; journal of applied phycology; biotechnology for biofuels and bioproducts; applied microbiology and biotechnology Concepts: lipid productivity; microalgae cultivation; microalgal biomass; biodiesel production; photobioreactor	4	3,895	11.3
38	Main fields: Life and earth sciences; Physical sciences and engineering Sources: desalination and water treatment; chemical engineering journal; journal of hazardous materials; journal of environmental chemical engineering; environmental science and pollution research Concepts: biosorption capacity; crystal violet; biosorbent dosage; removal of dyes; cationic dyes	4	7,576	11.2
4038	Main fields: Physical sciences and engineering; Life and earth sciences Sources: handbook of environmental engineering; proceedings of the 43rd industrial waste conference may 10, 11, 12, 1988; advances in industrial and hazardous wastes treatment; transactions of the imf; handbook of advanced industrial and hazardous wastes management Concepts: surface technology; Lenox Institute; European Academy; case histories; air flotation	3	36	10.5
1318	Main fields: Physical sciences and engineering; Life and earth sciences Sources: journal of hazardous materials; chemosphere; chemical engineering journal; environmental science and technology; the science of the total environment Concepts: hydrodechlorination; electrokinetic remediation; nZVI particles; voltage gradient; nZVI	3	1,241	10.5
1806	Main fields: Life and earth sciences Sources: bioresource technology; international journal of biological macromolecules; applied microbiology and biotechnology; journal of biotechnology; polymers Concepts: PHA production; polyhydroxyalkanoate production; PHA accumulation; production of polyhydroxyalkanoates; necator	4	538	8.2
3772	Main fields: Life and earth sciences Sources: journal of physics conference series; iop conference series earth and environmental science; jurnal presipitasi media komunikasi dan pengembangan teknik lingkungan; aip conference proceedings; iop conference series materials science and engineering Concepts: FPGA; simplex method; MATLAB; programming; adsorption	4	36	8.0
829	Main fields: Life and earth sciences; Physical sciences and engineering Sources: waste management; waste management & research the journal for a sustainable circular economy; journal of cleaner production; resources conservation and recycling; sustainability Concepts: bioreactor landfills; municipal solid waste management; landfill gas; MSW; solid waste landfills	4	1499	7.7

Examining disciplinary categories provides us with another way to understand how environmental biotechnology, as defined by our corpus, relates to other fields of science. Publications in the Dimensions database are categorised into fields of research (FoR) according to the Australia and New Zealand Scientific Research Council (ANZSRC) (Australian Bureau of Statistics 2020), which is a well-developed classification system covering all areas of science.[7]

Interestingly, only 3,429 publications fall into field 4103 (Environmental Biotechnology). The most prominent fields in the corpus are 4004 Chemical Engineering (28,145 publications), 4011 Environmental Engineering (24,725 publications), 4105 Pollution and Contamination (14,733 publications) and 3106 Industrial Biotechnology (10,104 publications) (Table 4).

Two probable explanations for the relative infrequency of field 4103 (Environmental Biotechnology) within our corpus are that the ANZSRC defined the bounds differently to those in EBNet's remit and that we have captured more relevant publications with our search using our definition of the field than the ANZSRC did within theirs.

The definition used in our search overlaps with that of the ANZSRC in most areas, such as bioremediation. However, in other areas there are differences - for instance biodiscovery is not included within our search, but is included within the ANZSRC's definition. Two notable differences where the ANZSRC definition is more restrictive are:

1) any genetic modification of organisms for industrial purposes is explicitly excluded from the ANZSRC's environmental biotechnology category (instead being classified as industrial biotechnology), even in the context where an industrial product is being produced from waste or pollutants.
2) any wastewater treatment processes are treated as chemical engineering, even if using purely biological methods. Although a publication may have multiple ANZSRC categories, in practice these publications tend to also lack the environmental biotechnology label where it could reasonably be expected.

It is likely that there are other such divergences between the ANZSRC definition of the field, and the field as defined within this report Moreover, it appears that there may also be a divergence between the field as defined in the ANZSRC guidelines, and what is labelled as such. Although not analysed quantitatively, some common scenarios where the environmental biotechnology field of research is under-applied are:

1) publications relating to bioremediation which do not explicitly contain the word "bioremediation".
2) publications relating to, activated sludge, anaerobic digestion, biochar or metal remediation.

Typically, these publications are instead tagged as chemical engineering and/or environmental engineering, with the pollution and contamination and/or industrial biotechnology fields also commonly utilised. Overall, though these tags provide a convenient manner in which to examine the environmental biotechnology field in relation to other fields, the environmental biotechnology

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[7] Seven other classification schemes are used within Dimensions, all of which either have a strong biomedical focus or are too coarse for our requirements - the ANZSRC is the only one of these schemes to have a category for environmental biotechnology (see Appendix 1).

ANZSRC field is underutilised within the corpus, even in core areas of interest to EBNet members. As such, strong conclusions based on analysis using these fields should be treated with caution.

Table 4 shows the top 20 fields of research (ANZSRC 2020, 4 digit), ordered by the number of publications in our corpus tagged with each ANZSRC field. The right-hand column indicates the % of the corpus that these publication make up.

Table 4. Top 20 most relevant fields of research (ANZSRC 2020, 4 digit) for environmental biotechnology publications in the last 5 years (2018-2022) and their % prevalence in our corpus.

Field	**Publications**	**% of Corpus**
4004 Chemical Engineering	28,145	14.01
4011 Environmental Engineering	24,725	12.30
4105 Pollution and Contamination	14,733	7.33
3106 Industrial Biotechnology	10,104	5.03
3107 Microbiology	9,578	4.77
4104 Environmental Management	7,962	3.96
4103 Environmental Biotechnology	3,429	1.71
3004 Crop and Pasture Production	3,335	1.66
3001 Agricultural Biotechnology	2,600	1.29
3103 Ecology	2,366	1.18
4102 Ecological Applications	1,638	0.82
3406 Physical Chemistry	1,593	0.79
4106 Soil Sciences	1,300	0.65
3002 Agriculture, Land and Farm Management	1,299	0.65
3108 Plant Biology	1,154	0.57
4016 Materials Engineering	1,001	0.50
4019 Resources Engineering and Extractive Metallurgy	999	0.50
3207 Medical Microbiology	916	0.46
3007 Forestry Sciences	863	0.43
3105 Genetics	792	0.39

This very different (ANZSRC) view of what “environmental biotechnology” is - including biodiscovery (see Appendix 1) - explodes the idea that there is one definition of environmental biotechnology as a field, and suggests that there are plural and conditional uses of the term (Stirling, 2010; Ràfols and Stirling, 2021).

What types of clusters can be found in the field of environmental biotechnology?

Environmental biotechnology encompasses a number of related (or less-related) research topics.

Term co-occurrence maps can be used to explore relationships among topics and conceptual structures. They draw on the whole corpus and map when two terms occur in the title or abstract of the same document, with proximity relating to the frequency with which terms appear together.

Figure 8 shows a term co-occurrence map illustrating some of the key words and phrases found in our corpus and how they relate to each other. The colours signify clusters of terms that relate to each other.

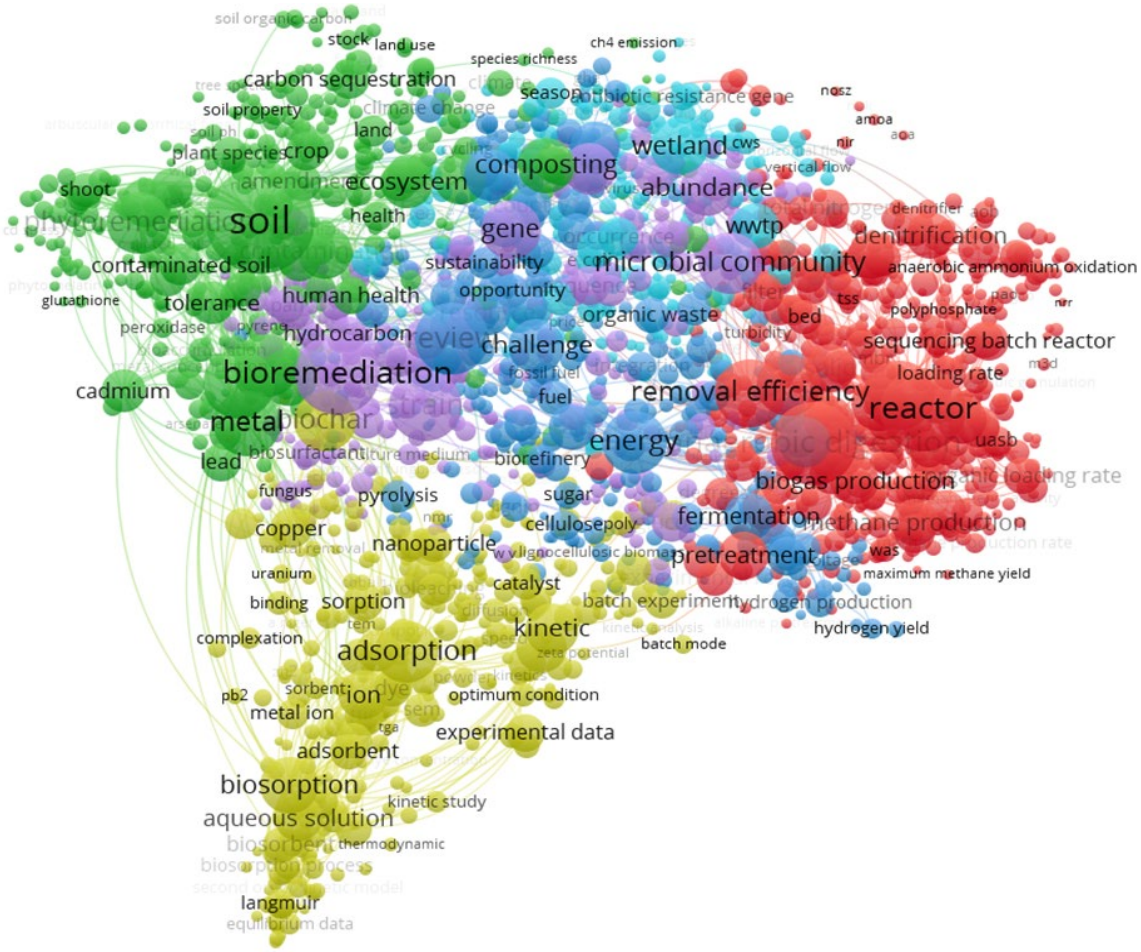

Figure 8. Term co-occurrence map created using VOSviewer, based on all publications from our environmental biotechnology corpus with at least 10 citations, binary counting, at least 150 occurrences of terms (3,599 terms), and keeping the top 60% of terms with the highest relevance scores (2,159 terms).

The term co-occurrence map provides a helpful overview on topics present within the corpus and their relations to each other. However, some terms may be too broad to be particularly meaningful (such as "sugar", "raw material" or "season"), or may only have a tangential relationship to the topic (for instance "human health" has relevance to bioremediation). As such, these maps are sometimes imprecise and ambiguous.

Field co-occurrence maps can also be used to explore relationships among topics and conceptual structures, but in this case based on the fields of research associated with each publication, instead of the terms found in publication titles or abstracts. Figure 9 shows prominent fields associated with environmental biotechnology, and how those fields relate to each other, based on how the environmental biotechnology publications in our corpus have been categorised over the last 50 years using ANZSRC four digit field codes (ANZSRC 2020) (as discussed in more detail in the previous section on how environmental biotechnology relates to the rest of science). The nodes on the map are located close to each other if the fields co-occur in documents frequently, and far away from each other on the map if they don't co-occur frequently.

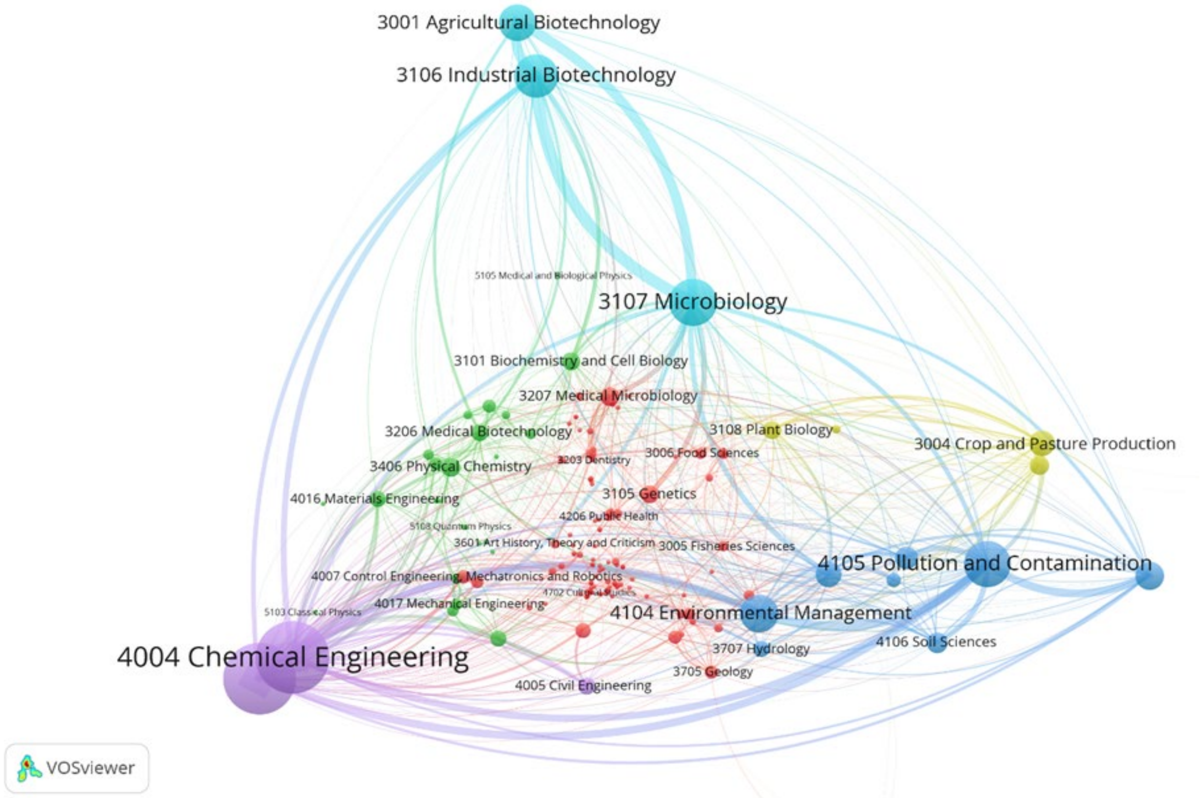

Figure 9. Field co-occurrence map created using VOSviewer, based on all publications from our environmental biotechnology corpus.

From the map in Figure 9, we can see that the field of environmental biotechnology is made up of various specialisms. Based on the co-occurrence of fields of research within publications, there is a wide variety of fields associated with environmental biotechnology, but there does not seem to be one core area to which all these specialisms connect. Some prominent fields include chemical engineering, industrial biotechnology and pollution and contamination. It is worth noting that these fields are among those that contained many publications meeting this report's definition of environmental biotechnology (see discussion prior to Table 4), which could explain the relative lack of prominence of the environmental biotechnology field itself.

This could also give some indication of what parts of the corpus are in which parts of this map. For instance, in the previous section, it was observed that wastewater treatment publications were frequently tagged as being chemical engineering, and the ANZSRC definitions and exclusions would imply that publications on the production of biofuels from waste would be classified as industrial biotechnology.

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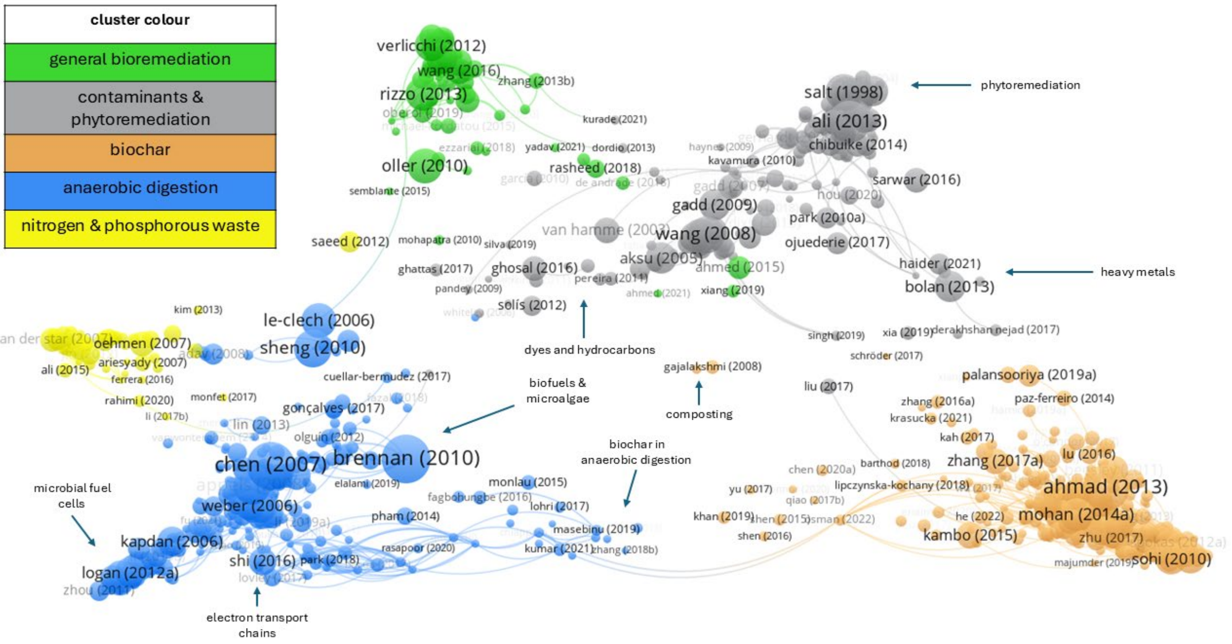


Figure 10. Bibliographic coupling map of environmental biotechnology publications (top 1000 from our corpus by total link strength based on citation similarity).

The map in Figure 10 is based on bibliographic coupling, where documents within the corpus share at least one common reference. Specifically, this map is based on the entire corpus of environmental biotechnology publications, selecting the top 1000 documents of 200,963 by total link strength, where there are a minimum of 100 citations per document. It therefore excludes any literature outside the corpus and those with low citation counts. When the corpus is plotted in this way, clusters of publications are generated using a clustering algorithm. The clusters are highlighted with different colours, which correlate with various topics. The relationships between topics in this map broadly align with those found in the term co-occurrence map (Figure 8). However, the selection criteria used may introduce biases in which publications appear on the map, which should be taken into account when interpreting data (see sections below on “How has the focus of research in these clusters changed over time?” and “Do different countries specialise in particular areas of environmental biotechnology?”).

The “contaminants & phytoremediation” cluster in grey can be found at the top-right of the map. This cluster contains documents on more specific topics - with phytoremediation documents at the top, documents on organic contaminants (“dyes and hydrocarbons”) at the bottom-left of the cluster and documents on heavy metal contaminants at the bottom-right of the rough triangle shape. These are marked by arrows on the map in Figure 10.

These various labels on the map are only approximate descriptors for various reasons. One is that the boundaries of the coloured clusters do not perfectly correspond with a change in topic - for instance there is a clear boundary between the green “general bioremediation” cluster at the top, and the grey “contaminants & phytoremediation” cluster at the top-left, but documents on pharmaceutical contaminants can be found both throughout the green cluster and in the bottom-left of the grey cluster.

Another reason to consider the cluster names as only approximate labels is that some topics do not form their own full cluster. An example of this is “composting” - spatially and cognitively distinct from the other topics, and located in the centre of the map, but algorithmically assigned to the orange “biochar” cluster at the bottom right.

The “biochar” cluster also demonstrates another limitation of the labels: a document may cover multiple topics, but may only be assigned to one cluster. For example, one document (located in the “biochar” cluster) relates to both “biochar” and “phytoremediation”; several other documents relate to “biochar” and “anaerobic digestion” (located in the right-hand part of the blue “anaerobic digestion” cluster at the bottom-left)

The “anaerobic digestion” cluster also contains documents on more specific topics. The very bottom-left contains documents on “microbial fuel cells”, with other documents on “electron transport chains” found near the bottom and centre of this cluster. Finally, the top-right of the cluster contains documents that are mostly about biofuels or microalgae.

The remaining two clusters relate to “nitrogen & phosphorous waste” (yellow, left) - with intermingled documents primarily on these topics, including anammox (anaerobic ammonium oxidation - a metabolic pathway converting ammonium and nitrite into diatomic nitrogen, which can be used in wastewater treatment); and to “general bioremediation” (green, top left), which includes documents relating to pharmaceutical waste, antibiotic resistance in waste, treatment of aqueous environments and treatment of wastewater or sludge, though also covering a variety of other topics.

There is no obvious central cluster, and the absence of one indicates a lack of evidence for practitioners directly referencing publications across all clusters of environmental biotechnology, and therefore of a shared “canonical” literature. In turn this suggests the clusters pictured likely developed mostly independently of each other. This does not imply that scientists lack a broader view of the field, or a sense of community across it, simply that it is not visible in referencing patterns over the last 50 years.

A final note is that some topics do not seem to share common reference bases and are to some extent dispersed across the map. Though there is a cluster of documents relating to wastewater treatment within the green cluster, for example, other documents on wastewater management appear in every single cluster. Another medium for treatment, soil, occurs frequently as a topic for publications, but documents relating to it are distributed across the entire right-hand side of the map.

Overall, using bibliographic coupling has allowed some of the cognitive links to be visualised on a map of environmental biotechnology publications. However, the basis for these relationships may vary between different areas of the map - such as a shared focus on removal of a specific contaminant (e.g. “heavy metals”), particular technologies (e.g. ”microbial fuel cells”) or a shared scientific basis (e.g. “electron transport chains”).

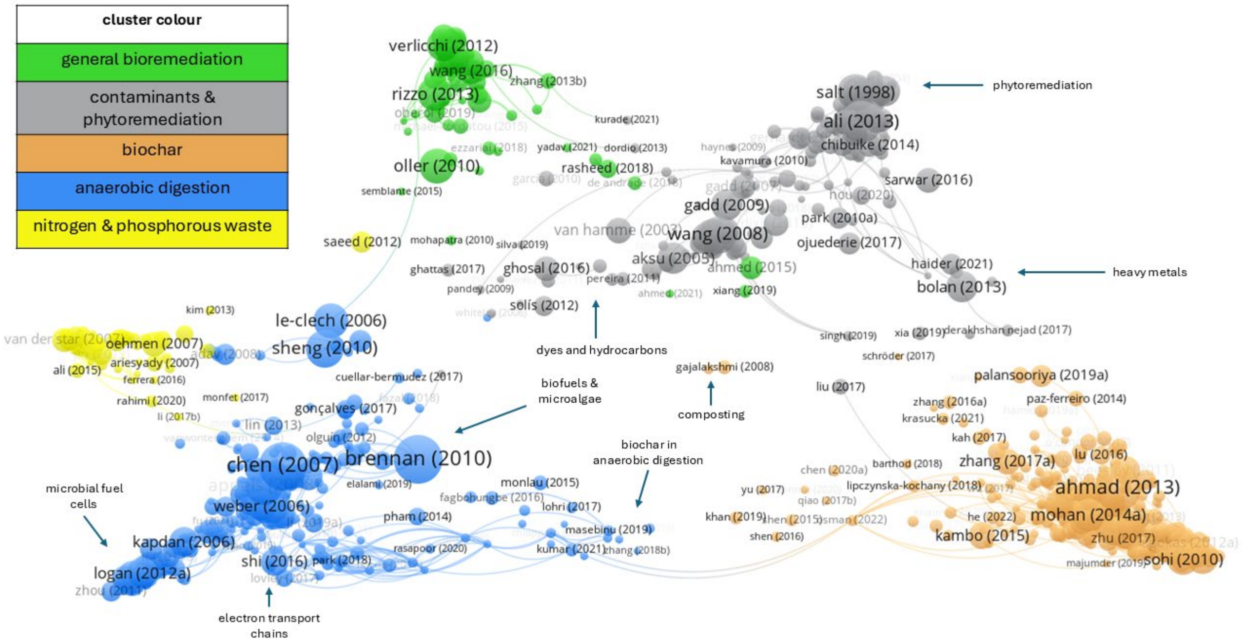
These may be conceptualised as different dimensions of cognitive similarity, in which one dimension is predominant in drawing together some clusters/regions of clusters but where another dimension may have greater influence on the clustering elsewhere. For example, the subcluster relating to “heavy metals” is primarily drawn together by a shared problem; the nearby “phytoremediation” subcluster primarily relates to a shared tool for resolving problems; and the “biochar” cluster relates to a shared material / object of study. Other such dimensions are the medium of study/intervention (e.g. soil/water), to what extent literature is basic or applied (e.g.

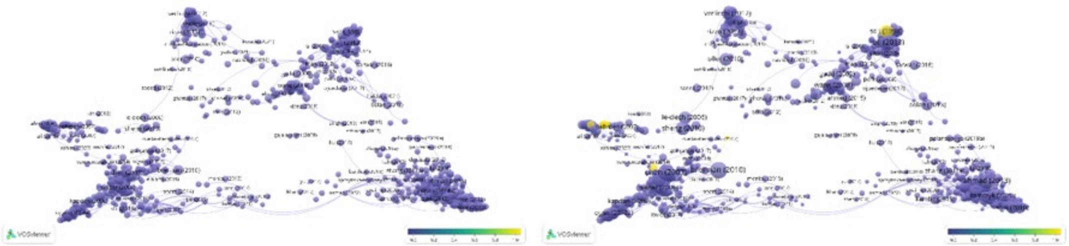
basic studies on biochar tend to be near the bottom-right) and products or organisms (e.g. the use of microalgae in anaerobic digestion systems and the production of biofuels from digesters occupy the same space within the "anaerobic digestion" cluster). This plurality of logics of classification or ontological objects (problems, materials, technologies, scientific phenomena) is a common limitation in bottom-up bibliometric techniques such as bibliographical coupling (Rafols, 2024).

These clusters therefore represent a compromise between different dimensions by which publications may be related. This does mean that sometimes there are clear cognitive links between sets of publications that may not be reflected on the map, simply because similarity in other dimensions had a stronger effect on the clustering. An example of this is bioremediation publications with a shared medium to be treated, such as water or soil, which only have a very loose arrangement in space on the map in Figure 10.

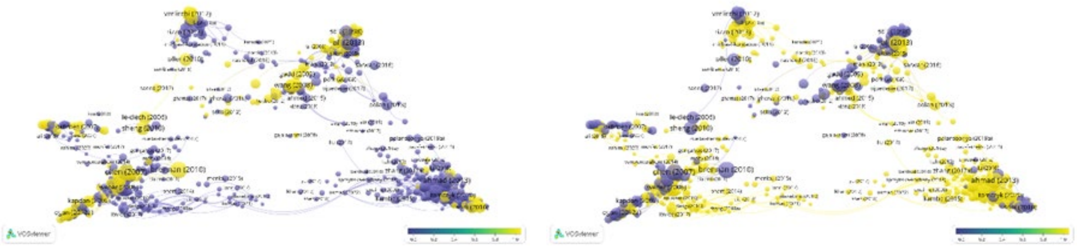
How has the focus of research in these clusters changed over time?

The maps in Figure 11 show four decades of environmental biotechnology research, overlaid onto the bibliographic coupling map of environmental biotechnology (Figure 10) discussed in the previous section. The nodes are coloured from purple signifying no environmental biotechnology research, to yellow indicating there was environmental biotechnology research.





1983-1992 1993-2002



2003-2012 2013-2022

Figure 11. Overlay maps based on the bibliographic coupling base map of environmental biotechnology publications to show the emergence of environmental biotechnology as a field over time. (Information in Figure 10 repeated for reference)

From 1983-1992, the map shows no environmental biotechnology research, although not all research is captured on this map since it is produced from a subset of relatively prominent publications. The publication trends in Figure 4 also showed that environmental biotechnology was a relatively small field during this period in terms of publishing. During the next decade, from 1993-2002, there were some publications in ”contaminants and phytoremediation”, “nitrogen & phosphorous waste” and “anaerobic digestion”.

After 2000, the volume of publications on environmental biotechnology increased (Figure 4), and from 2003-2012, there were publications in each of the main clusters on the map: “contaminants and phytoremediation”, “nitrogen and phosphorous waste”, “anaerobic digestion”, ”biochar”, and “general bioremediation”. In the final period, from 2013-2022, again, there were publications in each of the main clusters, particularly in the ”biochar” cluster, and to some extent in the “anaerobic digestion” cluster.

To what extent do those publishing in the field refer to the term “environmental biotechnology”?

As noted previously, only 881 of the publications in our corpus (total 200,963) use the term “environmental biotechnology” in their abstracts or titles. It is therefore not a term that is frequently used in the literature. There are similarities and differences between the characteristics of this sub-corpus (of publications using the term “environmental biotechnology” in their abstracts or titles – see Table 5) and the overall environmental biotechnology corpus (see Table 9). The top 3 countries are the same in both cases (although they appear in a different order). The top journals and top research organisations by number of publications (identified later in Tables 7-9 for the full corpus) are different.[8]

The difference in publication venue may also reflect that discussions of the field itself are taking place in different venues compared to the publication of primary research: of the top 3 journals only one (World Journal of Microbiology and Biotechnology) accepts primary research papers, while the others are dedicated to review articles (Current Opinion in Biotechnology) or are a handbook (Handbook of Hydrocarbon and Lipid Microbiology), respectively. It is relatively

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[8] A caveat to this is that the comparator data in the whole corpus is focused on the years 2018-2022, approximately half the publications, rather than the entire timespan of the corpus.

common in science for at least some higher-level commentary, including about a field of research such as “environmental biotechnology”, to be found in different sources (such as review articles, editorials, handbooks or book series) rather than in primary research articles.

Notably, two of the top three research organisations by number of publications (shown in Table 5) have organisational homes for “environmental biotechnology”: a “Department of Environmental Biotechnology” in Bharathidasan University and “Environmental Biotechnology Research group” and “Laboratory of Environmental Biotechnology” in Ghent. This recognition of the field by the research organisation may incentivise publications explicitly referencing the term.

Table 5. Features of the “environmental biotechnology” subcorpus

Variable	**Value(s)**
Timespan	1984:2022
Sources (journals, books, etc)	359
Publications	881
Document average age	13.2
Average citations per publication	34.4
Document types	
Research Article	474
Review Article	162
Research Chapter	228
Conference Paper	17
Journals, research organisations and countries	
Top 3 journals by number of publications	World Journal of Microbiology and Biotechnology (84), Current Opinion in Biotechnology (19), Handbook of Hydrocarbon and Lipid Microbiology (19)
Top 3 research organisations by number of publications	Bharathidasan University (26), Ghent University (10), University of Dundee (10)
Top 3 countries by number of publications	India (98), USA (96), China (72)

Figure 12 shows the location of “environmental biotechnology” in the term co-occurrence map from Figure 8. Unsurprisingly, it is relatively central to the field and co-occurs often with terms like “bioremediation”, “soil” and “biochar”. Also unsurprisingly, it is a relatively small node, compared to terms like “anaerobic digestion” or “phytoremediation” for example.

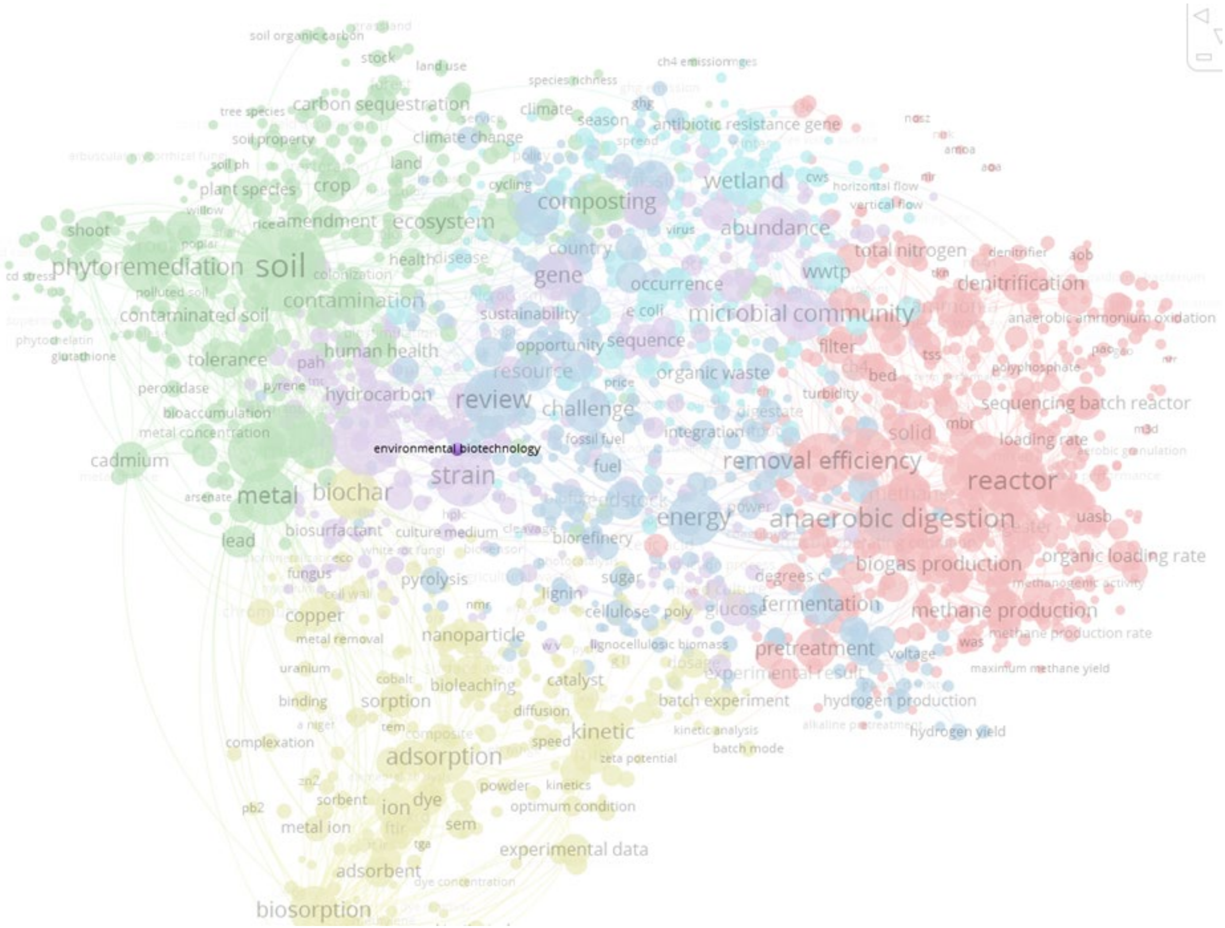

Figure 12. Term co-occurrence map showing the position of the term "environmental biotechnology". This map was generated from all publications with at least 10 citations, using binary counting, with at least 150 occurrences of terms (3,599 terms), and selecting the top 60% with the highest relevance scores (2,159 terms).

How does environmental biotechnology link with other related areas?

Within the corpus, we searched for the occurrence of the names of related or interconnected fields to identify overlaps and characterise where these fields are discussed. These fields are engineering biology, environmental engineering and industrial biotechnology and synthetic biology.

The results in Table 6 suggest that these terms are used infrequently in discussion, although all are present in the corpus. The relatively new term "engineering biology" only appears twice, reflecting relatively infrequent use of the term (so far) among the scientific community, in comparison to the more established and closely related term "synthetic biology".

Table 6. Features of subcorpuses of some related fields.

Search terms	Synthetic biology	Engineering biology	Environmental engineering	Industrial biotechnology
Number of publications in environmental biotechnology corpus	277	2	275	89
Number of publications in whole of science (Dimensions)	13,467	403	3,956	1,309
Proportion of publications found in corpus	2.1%	0.5%	7.0%	6.8%
Top 3 journals by number of publications	Biotechnology Advances (15), ACS Synthetic Biology (12), Microbial Cell Factories (7)	Journal of Computational Science) (1), Proceedings of ASME 2009 3rd International Conference on Energy Sustainability (1)	Canadian Journal of Civil Engineering (12), Water Science & Technology (11), Environmental Science and Technology (8)	Microorganisms for Sustainability (3), Environmental Microbiology (2), New Biotechnology (2)
Top 3 research organisations by number of publications	National Center for Biotechnology (11), Nankai University (9), Shanghai Jiao Tong University (7)	Newcastle University (1), University of Texas at Austin (1)	University of British Columbia (4), Tongji University (4), Duke University (4)	Indian Institute of Technology Delhi (4), Nanjing Agricultural University (2), Organisation for Economic Co-Operation and Development (2)
Top 3 countries by number of publications	USA (73), China (67), India (35)	UK (1), USA (1)	USA (47), China (46), India (26)	India (16), USA (9), Germany (8)

Environmental biotechnology publications contribute disproportionately to the literature using these terms, comprising 7.0% and 6.8% and 2.1% of publications using the terms “environmental engineering”, “industrial biotechnology” or “synthetic biology” respectively, versus only 0.18% of science as a whole. This implies a substantial overlap between environmental biotechnology and these fields. The data in Table 5 also implies that each overlap may be distinct as the top journals and research organisations for each subcorpus are completely different.

The biggest commonality between the subcorpuses, and with the overall corpus, are the top countries. Every country represented in the top 3 publishing countries of all subcorpuses is in the top 10 of the overall corpus (Table 10). Two subcorpuses even have the same top 3 as the overall environmental biotechnology corpus (albeit with the USA in 1st rather than 3rd place). The notable absence of China from the top 3 countries in the “industrial biotechnology” subcorpus likely reflects a lack of usage of the term in Chinese publications, rather than a lack of publication in the area, as highly cited papers that appear relevant to the field are present in the corpus.

That these related fields have distinct overlaps with environmental biotechnology is also evidenced by the top research organisations publishing within the subcorpuses (Table 5). Each subcorpus’ top 3 publishing research organisations have only one, in each case different, organisation in common with the overall corpus’ top 20 displayed in Table 9 (Tongji University for “environmental engineering”, 3rd in the overall corpus; Shanghai Jiao Tong University for “synthetic biology”, 12th in the overall corpus; Nanjing Agricultural University for “industrial biotechnology”; 20th in the overall corpus).

However, only in the “environmental engineering” corpus are there any top 3 journals in common with the overall corpus (Table 7), with Water Science & Technology (2nd in the overall corpus) and Environmental Science and Technology (10th in the overall corpus) to be found in both, perhaps indicating more overlap in the communities of practice between these two fields than between the others.

It is also worth noting that, unlike the “environmental biotechnology” subcorpus, the top journals within these related field subcorpuses are principally venues for primary literature, aside from Biotechnology Advances (containing review articles) and Microorganisms for Sustainability (a book series).

Which are the primary venues for research in this field?

Primary venues are those journals in which most environmental biotechnology research is published. Table 7 shows the total number of publications in the environmental biotechnology corpus in those journals, and the total number in all of science and environmental biotechnology publications as a percentage of publications in all of science for the last 50 years.

These patterns can change over time, as journals appear and disappear, or specialise as fields grow and divide. Table 8 shows the same results for articles from the last five years. “The Science of the Total Environment” is the most important journal in the field *in terms of number of articles published* in this period *(i.e. not taking into account impact)*. “Bioresource Technology” is the journal with the strongest specialisation in environmental biotechnology, with 41.8% of its publications in the field. “Water Research” (23.9%), “Journal of Water Process Engineering” (24.0%) and “Water Science & Technology” (26.5%) also show high levels of specialisation.

Table 7. Top 20 most relevant sources by number of environmental biotechnology publications in the last 50 years (1973-2022).

Sources	Publications - environmental biotechnology	Publications - all of science	Environmental biotechnology publications as a % of all publications
Bioresource Technology	8,864	27,462	32.3
Water Science & Technology	8,610	27,348	31.5
Water Research	5,258	22,359	23.5
The Science of The Total Environment	4,838	57,941	8.4
Chemosphere	4,282	40,495	10.6
Environmental Science and Pollution Research	3,676	34,396	10.7
Journal of Hazardous Materials	3,221	27,345	11.8
Journal of Environmental Management	2,612	16,712	15.6
Environmental Technology	2,290	8,299	27.6
Environmental Science and Technology	2,205	33,655	6.6
Chemical Engineering Journal	1,932	35,353	5.5
Journal of Cleaner Production	1,908	32,443	5.9
Applied Microbiology and Biotechnology	1,696	18,917	9.0
Huan jing ke xue= Huanjing kexue[9]	1,659	10,849	15.3
Waste Management	1,626	8,136	20.0
Applied and Environmental Microbiology	1,400	35,581	3.9
Environmental Pollution	1,397	20,419	6.8
Ecological Engineering	1,344	6,025	22.3
Water, Air, & Soil Pollution	1,302	13,174	9.9
Desalination and Water Treatment	1,299	15,509	8.4

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[9] This means “environmental science” in Chinese.

Table 8. Top 20 most relevant sources by number of environmental biotechnology publications in the last 5 years (2018-2022).

Sources	**Publications - Environmental biotechnology**	**Publications - all of science**	**EB publications as a % of all publications**
The Science of The Total Environment	3,612	33,718	10.7
Bioresource Technology	3,422	8,195	41.8
Chemosphere	2,334	16,010	14.6
Environmental Science and Pollution Research	2,046	22,956	8.9
Journal of Environmental Management	1,675	9,272	18.1
Journal of Cleaner Production	1,534	22,886	6.7
Journal of Hazardous Materials	1,367	10,709	12.8
Water Research	1,270	5,304	23.9
SSRN Electronic Journal	1,206	251,755	0.5
IOP Conference Series Earth and Environmental Science	1,101	83,261	1.3
Research Square	971	195,794	0.5
Chemical Engineering Journal	939	19,582	4.8
Journal of Environmental Chemical Engineering	813	6,892	11.8
Sustainability	797	54,069	1.5
Environmental Pollution	790	9,645	8.2
Water	705	15,719	4.5
Ecotoxicology and Environmental Safety	678	6,585	10.3
Journal of Water Process Engineering	667	2,774	24.0
Water Science & Technology	664	2,503	26.5
Frontiers in Microbiology	595	18,896	3.2

Which are the primary organisations publishing in the field?

Table 9 shows the top 20 research organisations by number of environmental biotechnology publications in the last 5 years (2018-2022). This is dominated by Chinese universities, mirroring the geographical distribution by country (see Table 10. The absence of any UK organisation is notable. At an institutional level, very few of these organisations specialise in environmental biotechnology (with the exception perhaps of the Research Center for Eco-Environmental Sciences, China with nearly 10% of publications falling within the environmental biotechnology field).

Table 9. Top 20 research organisations by number of environmental biotechnology publications in the last 5 years (2018-2022).

Research organisation	**Publications - environmental biotechnology**	**Publications - all of science**	**Environmental biotechnology publications as a % of all publications**
University of Chinese Academy of Sciences, China	1,325	129,601	1.02
Harbin Institute of Technology, China	1,093	53,332	2.05
Tongji University, China	867	47,676	1.82
Zhejiang University, China	790	95,157	0.83
Tsinghua University, China	629	81,722	0.77
Research Center for Eco-Environmental Sciences, China	611	6,393	9.56
North West Agriculture and Forestry University, China	582	15,952	3.65
China Agricultural University, China	568	20,925	2.71
Beijing University of Technology, China	551	19,414	2.84
Universidade de São Paulo, Brazil	545	83,138	0.66
Anna University, Chennai, India	534	37,333	1.43
University of Technology Sydney, Australia	496	22,860	2.17
Shanghai Jiao Tong University, China	482	94,875	0.51
Hunan University, China	441	25,278	1.74
Shandong University, China	439	48,868	0.90
Chongqing University, China	434	35,374	1.23
Technical University of Denmark, Denmark	429	22,992	1.87
University of Queensland, Australia	424	49,146	0.86
King Saud University, Saudi Arabia	413	34,383	1.20
Nanjing Agricultural University, China	412	15,165	2.72

Which are the primary countries publishing in the field and how has this changed? What is the state of international collaboration in environmental biotechnology?

Over the last five years, China has become *by far* the most productive country by the metric of number of publications in the field. Its emergence - as well as that of India (and to a lesser extent Brazil and South Korea) - is a recent phenomenon. Table 10 shows the number of publications with at least one author from each country for the last five years (2018-2022). It also shows the number of publications that are authored only by representatives of one country, and the number that are a result of collaborations with authors from at least one other country. Finally, the table shows the number of multiple country - authored publications as a % of all publications. In the top 10 for most publications, Australia (76.6%), the United Kingdom (72.9%), Germany (67.5%) and the United States (57.9%) show the highest levels of international collaboration. All are much higher than the leading two nations, for which only 29.8% (China) and 27.9% (India) of publications are co-authored with an international collaborator.

Table 10. Top 20 most productive countries by number of environmental biotechnology publications in the last 5 years (2018-2022) (for comparison, 18.1% of all scientific publications in Dimensions are multi-country authored).

Country	**Publications**	**Single country publications**	**Multiple country publications**	**Multiple country publications as a % of all publications**
China	24,926	17,508	7,418	29.8
India	9,468	6,827	2,641	27.9
United States	7,053	2,970	4,083	57.9
Brazil	3,212	2,314	898	28.0
Spain	2,856	1,407	1,449	50.7
United Kingdom	2,782	754	2,028	72.9
Australia	2,561	599	1,962	76.6
Italy	2,551	1,408	1,143	44.8
Canada	2,391	1,087	1,304	54.5
Germany	2,326	755	1,571	67.5
South Korea	2,232	885	1,347	60.4
Japan	1,988	845	1,143	57.5
Malaysia	1,934	811	1,123	58.1
Iran	1,876	1,204	672	35.8
Pakistan	1,799	498	1,301	72.3
Poland	1,680	1,084	596	35.5
Indonesia	1,606	1,288	318	19.8
France	1,539	528	1,011	65.7
Egypt	1,528	600	928	60.7
Saudi Arabia	1,379	163	1,216	88.2

The differences between countries are dramatic, with more than an order of magnitude difference in number of publications between the lead and 20th most highly-publishing country. In order to make the more subtle differences discernible, the map in Figure 13 adopts a logarithmic scale for publishing activity in each country (with 1 representing zero publications, shown in white).

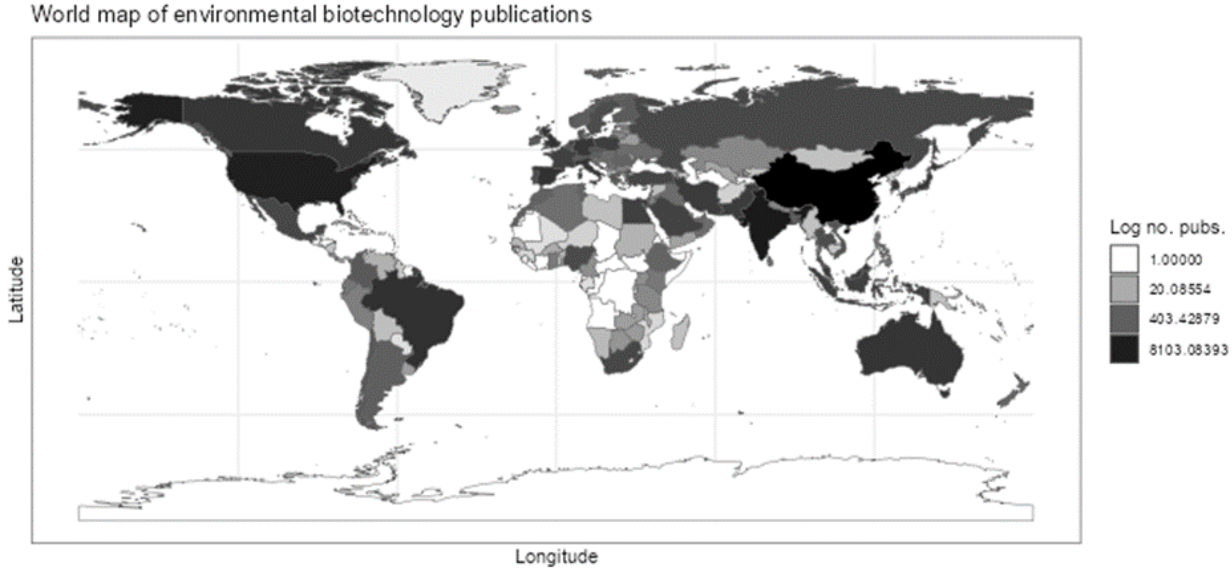


Figure 13. Publishing activity in countries of the world (logarithmic scale, based on results in Table 10 above)

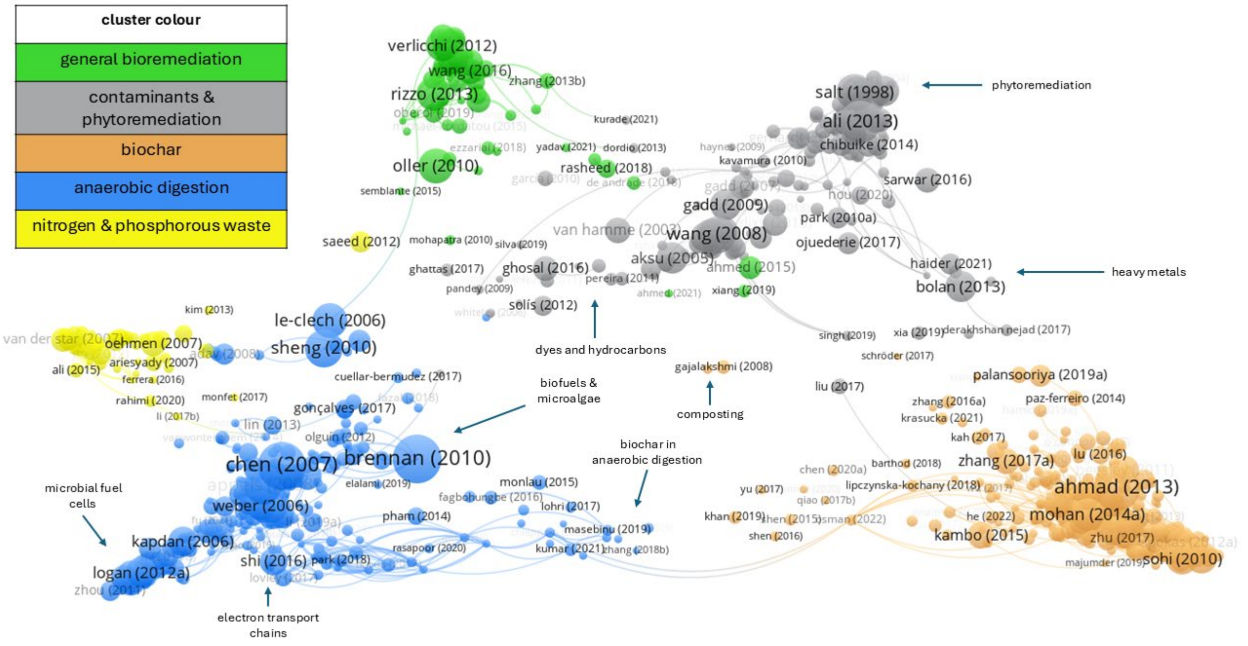
Do different countries specialise in particular areas of environmental biotechnology?

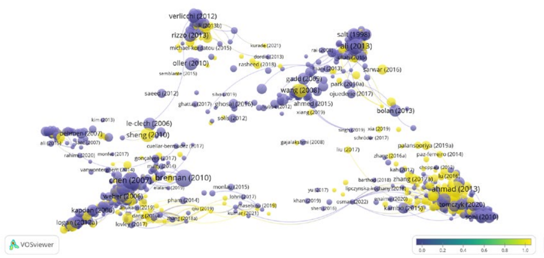
Figure 14 presents overlay maps shows the publications in our base map (Figure 10, repeated for reference) with authorship from particular countries. Within the top six countries in terms of publications, we can see varying publication patterns - with China being notably generalist and the USA being notably specialist.

Even China has some small degree of specialisation, as it appears to be somewhat more active in biochar than in other subject areas, and somewhat less active in the “contaminants and phytoremediation” cluster. Notably, its overlay map bears a strong resemblance to the 2013-2022 overlay map in Figure 11 - indicating a higher volume of publication in recent years. Despite its relative lack of contribution to the “industrial biotechnology” subcorpus, some of the key publications in the “anaerobic digestion” cluster relate to the topic.

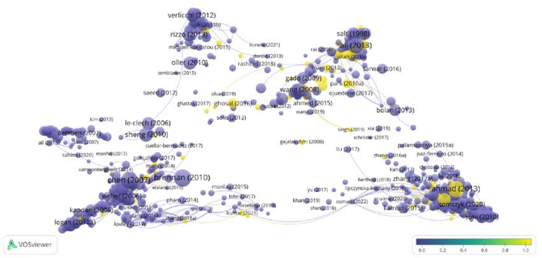
In contrast, the USA, although active to some degree in most subject areas mapped, appears to have a strong focus on “anaerobic digestion” and, to a lesser extent, “phytoremediation”, and its overlay pattern bears a loose resemblance to the 2002-2013 overlay map.

The remaining countries, except Brazil, appear to have maps that are somewhat generalist, but with notable areas where publications are relatively sparse.

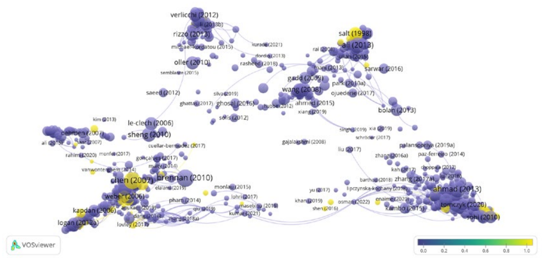




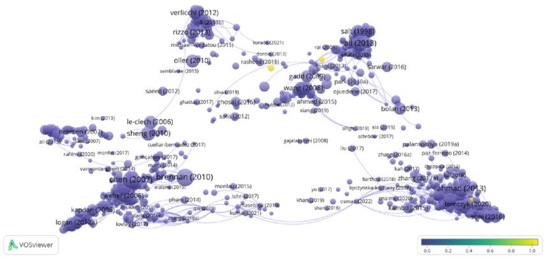
China



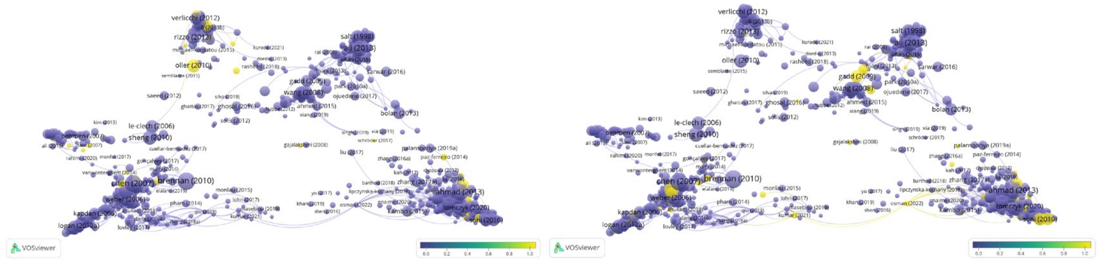
India



USA



Brazil



Spain UK

Figure 14. Overlay maps based on the bibliographic coupling base map of environmental biotechnology publications to show the specialisation patterns of the top six countries publishing in environmental biotechnology. (Figure 10 repeated above for reference)

India’s overlay map bears a loose resemblance to the 2013-2022 overlay map, perhaps indicating a higher proportion of publications in the last decade, but is also notable for its relative sparsity of publications in the “anaerobic digestion” cluster (and associated topics) and the “nitrogen and phosphorous waste” cluster.

Spain has publications scattered across the map, with publications in the “biochar” and ”dyes and hydrocarbons” clusters, but has a near total lack of publications relating to “phytoremediation” or to “heavy metals”.

The UK shares Spain’s lack of phytoremediation publications and its focus on “biochar”, although notably including some of the older prominent papers in the field; but it appears to produce relatively few publications on “nitrogen and phosphorous contaminants”.

Finally, while Brazil produces more publications than Spain and the UK, it has fewer publications visible in the overlay map - perhaps indicating fewer highly cited publications within the field versus the other five countries surveyed. This is possibly an effect of bias in the selection criteria for the base map, as what publications are visible relate to “biochar” and “general bioremediation”.

Notably, all six countries have overlapping but distinct publication patterns when mapped in this way. China’s, and to a lesser extent India’s, publication pattern resembling that of publications in general over the last decade suggests a growing role within the field; and the lack of similarities between the UK, Spain and the USA maps indicates distinct research priorities within the West when it comes to environmental biotechnology.

Insights into the patterns of publication offered by the bibliometric study can be further interpreted in combination with qualitative data, which is introduced in the following section (Current Dynamics and Debates in Environmental Biotechnology - Interpreting the Bibliometric and Qualitative Data). A draft of this section was shared in advance of the workshop on 4th November 2024, whereas the final section (Futures of Environmental Biotechnology) built upon the discussions at that workshop.

5. Current Dynamics and Debates in Environmental Biotechnology - Interpreting the Bibliometric and Qualitative Data

Twelve interviews were conducted with stakeholders across the environmental biotechnology community including a range of scientists, engineers and private sector actors. Interviews are anonymised but where quotes are presented, we include the date (day/month/year). These interviews focussed on a qualitative interrogation of histories and current dynamics of environmental biotechnology in the UK and (to a lesser extent) internationally, and help to shed light on some of the bibliometric findings. For many of the interviewees, the most relevant contemporary dynamics in the UK revolve around increasing investment in “synthetic biology” and “engineering biology”. The UK government has a history of investing resources in these areas (Marris 2015; Marris and Calvert 2020).

The “Synthetic Biology for Growth” (SBfG) programme, totalling £102 million, originally ran from 2014 to 2020, and saw extended investments to 2022. The partners involved - Biotechnology and Biological Sciences Research Council (BBSRC, lead), Engineering and Physical Sciences Research Council (EPSRC), Medical Research Council (MRC) - have more recently joined with the Natural Environment Research Council (NERC), Department for Science, Innovation and Technology (DSIT) and Defence Science and Technology Laboratory (Dstl) in adopting the terminology of “engineering biology” in their investments. Modelling of impact to 2032 in a recent evaluation of the SBfG programme found “a return on investment (RoI) of between 2.9 and 3.4 times the initial investment (including economic multipliers)” (EKOS/Optimat 2024).

The National Engineering Biology Programme aims to create a coherent engineering biology community and ecosystem and provides the overarching framework in this area. Recent investments have drawn on the Technology Missions Fund (a “£320 million programme designed to accelerate technology development, adoption and diffusion, and cement the UK’s global leadership in five technologies of UK strength and opportunity” UKRI 2024a) to the tune of £60 million, and a further £65 million of UKRI core funding to support:

- Mission Hubs in engineering biology (£70 million investment, five years duration) - of particular note in this context is the Environmental Biotechnology Innovation Centre (EBIC)
- Mission Awards (£30.4 million investment, 24 months duration)
- Collaborative research and development (£13.5 million investment, 18 months duration)
- Seed corn funding (£4 million investment, two years duration)
- Proof of concept activity (£3 million investment, two years duration)
- Accelerator Feasibility Awards (£2 million investment, two years duration)

(UKRI 2024a)

As well as EBNet colleagues, we talked to others who were involved in EBIC (beyond the 4 out of 5 EBNet Co-Is who are also EBIC Co-Is), allowing an exploration of the interface between the more traditional areas of environmental biotechnology and those associated with engineering biology. Some recurring themes that arose during these interviews are discussed below, with questions that provoked debate at the workshop on 4th November.

A field or not a field? That is not the question

Combining the bibliometric study above and our interview data it is possible, as stated in Section 1, to understand “environmental biotechnology” as a field. However the study was not asking “is it a field?”. It is not our goal to provide a definitive or objective definition of “environmental biotechnology,” but to illustrate plural and conditional views about what the field is. In mapping environmental biotechnology as a changing field, we also need to be aware of how our methods and assumptions influence our understanding.

In some ways, environmental biotechnology can be conceptualised as a hollow “doughnut”: our bibliographic coupling map in Figure 10 shows a circle of activity around a gap in the middle. This bibliometric approach suggests the absence of a shared “canonical” literature (at least in our corpus) to which all clusters of environmental biotechnology are associated. In turn, as discussed above, this suggests the clusters probably developed independently from each other in most cases.

This resonates with some of our interview data, which shows that EBNet members do not necessarily identify as environmental biotechnologists but with particular clusters. Several interviewees admitted to having a somewhat limited awareness of activity outside of their particular area of interest or expertise, although in some cases this was attributed to an interviewee’s relatively recent entry into the field (and hence a relatively low awareness of current or historical activity). Nevertheless, one more experienced member of the EBNet community asserted that “the field itself is really broken up into a series of cottage industries working more or less in parallel without much communication” (interview, 8/8/2024).

The category (or at least label) “environmental biotechnology” does, however, play a role in bringing together these clusters, mobilising resources or organising collaboration or instruction. EBNet itself is a prime example (and EBIC could also be seen this way). The “Environmental Biotechnology Division of the European Federation of Biotechnology”, the Ghent “Environmental Biotechnology” Laboratory and Research Group, and the “Bharathidasan University Department of Environmental Biotechnology” are other examples (see section on “To what extent do those publishing in the field refer to the term “environmental biotechnology”?” and Table 3).

While in most cases interviewees, particularly scientists and academics, agreed that some or most of their work could be called “environmental biotechnology,” and themselves identified with the term, its use appeared to be situationally contingent, and counted as one of several professional designations that they might identify with, whilst at other times identifying with industrial biotechnology or engineering biology, for example.

The strange case of the absence of environmental biotechnology

In some ways, environmental biotechnology can be considered a neglected underdog of a field. The term “environmental biotechnology” is relatively absent from our data (it appears in less than 0.5% of papers in our corpus) and the field (at least when labelled “environmental biotechnology”) has not benefited from the kinds of investments that have been attracted by synthetic biology or engineering biology discussed above.

One of our interviewees argued that the field of environmental biotechnology has been “underrated” because “it's not regarded as exciting, it's not regarded as glamorous,” and consequently “the sheer size of its contribution is not always recognised, and how essential it [is] not always recognised” (interview, 30/7/2024).

Several interviewees seemed to have found themselves within the field of environmental biotechnology by accident (interviews 2/8/2024, 8/8/2024), with only a minority having studied it or seen it as a desired destination.[10] This lack of attractiveness (especially for early career researchers) may be a failure in "marketing" of the field, that arguably dates back to the selection of the term "activated sludge" to describe a technology that would revolutionise civil engineering's contribution to public health.

However, it may also have economic dimensions. Traditional environmental biotechnology (e.g. wastewater management) is often a public good (a non-rivalrous service that is available to all in a particular society), and one that requires public sector investment, underpinned by regulation and policy to create infrastructure and markets for products and services (for example the US Superfund, highlighted in the section on "The History of Environmental Biotechnology"). As such, environmental biotechnology may not traditionally have been as amenable to entrepreneurial innovation as others (e.g. pharmaceuticals) which rely less on regulation and policy to create market demand[11], and offer substantially greater returns in high income markets. It may alternatively (or in addition) be due to the fact that more traditional environmental biotechnology innovations (e.g. microbial communities - generation 3.0) are not as amenable to intellectual property protection/ patenting as pharmaceuticals, or indeed genetically-modified microorganisms (generation 4.0) and thus have traditionally received less private sector investment or policy attention by governments prioritising economic growth.

The different logics of synthetic biology and environmental biotechnology

Our interviews suggested that synthetic biology and environmental biotechnology work with different logics of engineering and different logics of the problems they are trying to solve (building foundational technologies/interchangeable parts vs dealing directly with real-world problems). One of our interviewees (8/8/2024) described synthetic biologists as follows: "they have a very mechanistic, Meccano view of the world where X plugs into Y, that's what an engineered system is. And that's not what engineered systems are in the real world."

The same interviewee summarised what they consider to be the challenges of applying engineering principles to biological systems in environmental applications:

> *"It's not about manipulation, it's about making things work and how, and that particularly means how you deal with ignorance and how you can't. So, especially in the environment, you have to be able to make things work in a state of partial understanding. And arguably all engineering is actually achieved in the face of partial understanding"*

(interview, 8/8/2023)

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[10] This may relate to the scarcity of departments or courses bearing the name "Environmental Biotechnology". More senior colleagues are particularly likely to have trained in other disciplines before the term "Environmental Biotechnology" became more widely-used.

[11] The pharmaceutical sector is obviously very tightly regulated, however policy and regulation is not required to create market demand. Wealthy individuals will pay for medicines, whether or not the government intervenes. However government intervention (e.g. the Superfund example) is necessary for polluters to pay penalty fines, which can be used to create demand for clean-up.

Environmental biotechnology recognises that perfect understanding and control are not achievable. It works with dirty, mixed cultures and recognises the complexity of real-world systems in understanding the viability of engineered organisms outside of controlled laboratory conditions.

Environmental biotechnology ‘works’

An interviewee with an engineering background argued that the defining feature of a technology was that it “works”, and that “working” was distinct from “knowing” or “understanding”. He saw a conflict between the incentive structures of academia and this idea of a technology 'working':

> "*the complex systems are incredibly complex and still very theoretically poorly understood, but they work very well, whereas the simpler systems are in theory better understood, but in fact, often don't work well at all. So you remember, as an academic, something doesn't have to work. It just had to be published. And so there's a misalignment of incentives there.*"
>
> (interview, 8/8/2024)

The implication of this statement is that there are many fields of science - including 'engineering biology' - in which 'to work' is not the main priority. The same interviewee argued that this was connected to the different approaches to engineering discussed above. For instance, a mantra that they used in their teaching was an old - and possibly apocryphal - quote attributed to a civil engineer (Dr. A. R. Dykes, British Institution of Structural Engineers):

> *“Structural engineering is the art of modelling materials we do not wholly understand into shapes we cannot precisely analyse so as to withstand forces we cannot properly access in such a way that the public at large has no reason to suspect the extent of our ignorance.”*

In contrast, synthetic biologists often say their ‘motto’ is the quotation attributed to Richard Feynman *"what I cannot create, I do not understand"* (Calvert 2013).

Is environmental biotechnology metamorphosing?

As discussed above, the phrase “environmental biotechnology” rarely appears in the bibliometric corpus of publications, aside from its use in review articles, and has not been used as a label for recent research investments. However, one recent use of the phrase in the UK has been in the Environmental Biotechnology Innovation Centre (EBIC). This was one of six Engineering Biology Mission Hubs (see above) funded, and is the only hub using the specific term “environmental biotechnology.” The EBIC hub positioned itself in the mission area theme “environmental solutions,” and has framed its environmental biotechnology work as applications of engineering biology, raising questions about the distinctions discussed in the above two sections.

Other hubs - like the “Engineering Biology Hub for environmental processing and recovery of metals” and the “Preventing Plastic Pollution with Engineering Biology (P3EB) Mission Hub” were positioned across the theme “environmental solutions and clean growth”. No fewer than 8 of the 23 smaller mission awards fell within the “clean growth” theme, with 2 further awards falling within the “environmental solutions” theme (UKRI 2024b).

It is currently unclear what this integration of environmental biotechnology and engineering biology will mean in practice, however the field is likely to metamorphose if "environmental biotechnology 4.0" becomes a reality, and if the ambitions of "environmental biotechnology" extend from more local challenges (e.g. pollution) to more global (e.g. climate change) or systemic (e.g. circular economy, clean growth) challenges. The potential, or even need, to incorporate engineering biology tools to meet the challenges targeted by environmental biotechnology was mentioned several times in interviews with EBIC members, with one Co-I noting that "we've gotten to the point where we don't think that conventional engineering will get us where we need to be […] and this is where we feel that engineering biology gives us that little boost" (interview, 16/9/2024) However, it is important to note that many of the EBIC Co-Is still understood there to be a clear distinction between the two terms, essentially arguing that "synthetic biology can be environmental biotechnology if it's applied to an environmental problem," whereas the term environmental biotechnology could refer to the broader practice of using both engineered or "the natural – the wild type, essentially – version of an organism, [to do] something that it would do naturally" (interview, 8/8/2024).

A shift in focus, or emphasis, in environmental biotechnology requires investment in research, but also significant policy and regulation to drive particular directions of innovation, for example to substitute (environmentally-damaging) chemical or industrial processes with biotechnologies. In the USA, a totemic document promoting this vision was the White House (2023) report "Bold Goals for U.S. Biotechnology and Biomanufacturing: Harnessing Research and Development to Further Societal Goals." In the UK, under the Sunak government in December 2023, former Science Minister Andrew Griffith announced a national vision for engineering biology (DSIT 2023a; 2023b), setting out a £2 billion funding package to position the UK at the forefront of this emerging field. This decision also established a group bringing together policy-makers and academic researchers with industry leaders and experts, who would steer the government's approach (DSIT 2024).

These and related themes, and the ways in which they will shape the potential futures of environmental biotechnologies in the UK, were discussed at the workshop on 4th November 2024, and offered some preliminary perspectives on the future (or futures) of the field. Summary notes of these discussions are included in Appendix 3. As agreed at the outset of the workshop, we do not attribute any points made to individual speakers.

6. Futures of Environmental Biotechnology

The futures of environmental biotechnology, and indeed its definitions, are open. Substantive consideration of their possibilities and implications is beyond the scope of this project and requires dedicated research and funding (see Section 7). However, below, we identify some of the issues and concerns that were raised in the workshop and through the course of this research, as they relate to the futures of the field.

Delineating the boundaries of the field

Delineating the boundaries of environmental biotechnology is difficult within a context in which it is metamorphosing. At the same time, the motivations for doing so deserve reflection. There are reasons to adopt the term "environmental biotechnology" as a tool for bringing together the community and mobilising resources into the future (see Appendix 3, Table #5). More generally, better identification of the field and the need to overcome siloing of academic expertise were identified as challenges for environmental biotechnology. But there may also be reasons to set boundaries that exclude particular activities.

Discussion at the workshop referred to the "long shadow" of the GM controversy on the environmental applications of biotechnology. A possible response would be to consider approaches that delineate what is *not* environmental biotechnology. Gene-editing, genetic engineering, gene drives and other technologies raise concerns about ownership, hype and risks, and environmental biotechnology as a field (at least up to the third generation) may attempt to separate and distance itself from these technologies in order to avoid inheriting these challenges. Some participants at the workshop (see Appendix 3, Table #5) also suggested that methods such as sequencing and "omics" might be what brings the field together, arguing that some methods that are now used in adjacent fields and more widely were pioneered in environmental biotechnology.

Elsewhere, interviews and workshop discussion (Appendix 3, Table #4) suggested that environmental biotechnology might focus on delivering environmental benefits through waste management (with potential valorisation of waste streams as a side consequence), rather than relying on waste streams for the production of new raw materials or industrial feedstocks. As discussed below, the distinction between these approaches is complex, but careful consideration of these issues may help ensure that "environmental biotechnology" does not become associated with the continued production (lock-in) of waste.

Whilst there may be a rationale for delineating the field of environmental biotechnology along these or other lines, it is worth noting that boundary-setting of this kind requires significant intellectual and other resources and is unlikely to succeed without them.

Moderating Environmental Biotechnology's Contribution to Waste and Consumption

Interviews and discussions at the workshop highlighted the waste hierarchy and the primary aim of regulation being to reduce waste (Appendix 3, Table #4). One interviewee, for example, suggested that the need for early applications of environmental biotechnology (Chakrabarty's work at General Electric) had been lessened by regulation that had led to prevention of oil spills (e.g. through double-hulled tankers) (interview 6/9/2024).

Several interviewees discussed the issue of waste valorisation and the use of waste as a cheap feedstock in industrial supply chains. While there was widespread acknowledgement that this practice could create perverse incentives which led to the persistence – or lock-in - of inefficient or wasteful practices, or even an increase in overall waste production as a means of securing a cheap, valuable feedstock, interviewees also stressed that complete elimination of waste is unrealistic (also discussed in the workshop - see Appendix 3, Table #4). For example, one interviewee (17/9/2024) pointed to numerous food and drink production processes, such beer brewing (spent grain) and sugar production (sugar beet pulp), which produced organic waste products and which further process improvements were unlikely to eliminate. Instead, they argued that there is a responsibility to find "intelligent way(s) to make use of that waste so that [we can] extract something out" (Interview, 17/9/2024). Other respondents made similar points about wastewater and sewage production (Interview, 2/8/2024), arguing that while efforts should always be made to reduce initial waste production, "as your population grows, the amount of sewage you have grows. There's just no escape from that." Likewise, environmental biotechnology could, in some cases, contribute to increased consumption of new products derived from waste streams. Instead, the challenge for scientists – and society as a whole – was to find a way to “valorise and maximise things that people are going to consume anyway” (Interview, 2/8/2024).

Understanding Ownership, Access and Directions of innovation

Several interviewees and workshop participants (e.g. Appendix 3, Table #5) described working in a context of limited funding. In the absence of public sector investment, private sector funding (with proprietary ownership) was seen to play an important role, although working across the private-public sector boundaries raised challenges associated with different institutional incentives and between industry and academia (Appendix 3, Tables #2, #3).

The role of intellectual property (in a traditionally “public good”/ “public benefit” field) is ambiguous. It was recognised that IP protection can have multiple functions and can make knowledge more transparent, as well as in some cases restrict the use of this knowledge (See Appendix 3, Table #3). The practicalities of licensing and of copyleft were also discussed by our workshop participants, as well as how intellectual property concerns may have contributed to the GM controversy. Participants also questioned what kinds of environmental biotechnology were appropriate for intellectual property protection or private ownership, with some indicating specific research areas or making a distinction between infrastructure and products.

The source of funding/ investment also has implications for the directions from which innovation is likely to emerge. Private sector firms may be more likely to focus on “excludable” technologies that increase competitiveness. This favours developing biotechnologies to remediate the environmental impacts of certain (environmentally-harmful) products/brands over others, making them more ’palatable’ to an increasingly environmentally-conscious consumer. For example, one respondent was asked about industrial partners funding research into developing waste treatment tools for a particular family of commercial products: would the development of these proprietary technologies give a particular firm a competitive advantage over those who used different materials or chemical components in their own products? While acknowledging this scenario as a possible risk, the interviewee focussed on the importance and necessity of such (environmental biotechnology) work in a broader sense, noting “if you don't get academic help to solve these problems, it's not like they're going to go away, right? Consumers will consume and most of them aren't going to go 'I'm not going to buy deodorant because I'm polluting the environment” (interview, 2/8/2024). These types of considerations were discussed at the workshop (Appendix 3, Table #4), with participants being aware of the danger of environmental biotechnology being used in greenwashing, and recognising the need for strong regulation to prevent this.

Applications for resource-poor contexts were also thought to be less likely to emerge from private sector investment. Some workshop participants and interviewees highlighted the unrealised potential for established environmental biotechnologies in developing countries (e.g. Appendix 3, Table #4) and called for policies to increase access to such technologies, and to support directions of innovation that responded to challenges in these specific contexts.

Crafting Context-Sensitive, Agile Regulation for Environmental Protection

Many interviewees and workshop participants (e.g. Appendix 3, Tables #1, #2, #4) identified the need for better regulation, particularly to balance risks and benefits of innovation, provide standards that could enable the field to progress and ensure access to technologies in low income/ resource-poor contexts.

Participants highlighted the need to adopt the waste hierarchy (making products and processes low waste, low risk or recyclable-by-design, rather than focussing on the “end of pipe” recycling of wastes) in a context-sensitive, technology-agnostic/ technology-neutral way. This could contribute to environmental improvements through a combination of low-tech approaches, (proven) environmental biotechnologies and/or emerging engineering biology approaches, depending on the context (Appendix 3, Table #1).

According to the workshop discussions, regulatory frameworks and categories need to be dynamic and responsive to changing technologies and their impacts on supply chains, guarding against perverse incentives or lock-in to the continuation of waste streams. Risks and benefits (beyond life cycle analysis) need to be considered holistically, especially in contexts of uncertainty associated with emerging pollutants and technological change. These challenges are far from simple and require dedicated interdisciplinary research.

Participants also emphasized stringency and enforcement of regulation, whilst stressing the importance of context. In the UK, for example, participants cited legal changes that will see UK water executives face prison if they pollute waterways (The Independent 2024), which might alter demand for biotechnological treatment. Some participants highlighted the absence of capacity for implementation and enforcement of such policies in certain contexts as a barrier to the application of environmental biotechnology (exacerbated by a lack of access due to limitations in knowledge and finance). In other cases, regulation and standards in richer (importing) countries may have negative impacts in poorer regions (Appendix 3, Table #4). This prompted calls for international co-ordination and a consideration of policy impacts beyond national borders.

Collaboration Across Contexts - Local and International Futures of Environmental Biotechnology

Our bibliometric analysis shows different specialisations, and varying degrees of international co-authorship, across the countries we studied. The participants gathered at our workshop broadly favoured greater international collaboration in both science and policy, including co-ordination around intellectual property and biosafety, where divergent regimes exist (Appendix 3, Tables #3, #4).

Environmental biotechnology represents a growing global market and a focus for scientific and technological competition. However, its potential applications to various UN Sustainable Development Goals also call for international collaboration. Interviews suggested the need for more UK funding to international consortia in this area (akin to physics megaprojects like the LHC), and workshop participants offered specific opportunities for the UK to contribute to co-ordination efforts, such as the World Water Congress in Glasgow in 2026.

Regulatory co-ordination efforts are underway at various levels. The Organisation for Economic Cooperation and Development (OECD 2024a) produces consensus documents around regulatory assessment of biotechnology products which are “intended to be mutually recognised among OECD member countries”. At the same time, as discussed at various times at the workshop (Appendix 3, Tables #1, #4) context matters, and regulatory approaches in OECD countries may be inapplicable in other contexts. Some participants suggested that potential policy/regulatory scenarios associated with current and future environmental biotechnologies should be extended to include more diverse contexts. This is particularly important where innovations, such as genetically modified organisms, may not obey national borders or where risks and benefits are subject to divergent understandings (Van Zwanenberg et al 2011).

Balancing Hope and Hype, Opportunities and Challenges, in Generation 4.0

At our workshop, the potential application of genetic technologies to microbial genomes (and those of other organisms i.e. beyond the water focus of Box 1) was seen to present a number of opportunities and risks, especially when combined with other technologies. (See Appendix 3, Table #2). At the same time, participants also recognised a degree of hype surrounding the possible next generation of environmental biotechnologies (Appendix 3, Table #4). UK and US policy documents cite analysis (McKinsey Global Institute 2020) suggesting that biological production/ synthetic biology applications could have direct economic impacts of up to $4 trillion a year over the next 10 to 20 years. The White House (2023) puts forward the ambition that in the next 20 years, the US will "demonstrate and deploy cost-effective and sustainable routes to convert bio-based feedstocks into recyclable-by-design polymers that can displace >90% of today's plastics and other commercial polymers at scale" and "produce at least 30% of the U.S. chemical demand via sustainable and cost-effective biomanufacturing pathways". These ambitions are to be welcomed, but the systemic changes they require should not be underestimated.

As the scope of the "environment" targeted by environmental biotechnology expands, and global sustainability challenges become more urgent, the allure of (over-hyped) theoretical contributions of the next generation of environmental biotechnologies may increase. Karabin et al (2021) have investigated websites of synthetic biology firms in the USA, finding that "sustainability is a visible part of the self-presentation of the nascent synthetic biology industry". Identifying particular framings of sustainability in these presentations, they suggest that the industry "engage in explicit deliberation about its approach to sustainability". We suggest this would also be worthwhile for environmental biotechnology , in order to explore different visions and imaginaries of the role of biotechnology in environmental protection (and restoration) and to ensure that over-hyped claims do not detract from the demonstrated benefits associated with existing approaches.

7. Limitations of this Project and Possibilities for Future Research on Environmental Biotechnology

Deeper bibliometric analysis of the field

Technical and time considerations meant that we could not use the full potential of our corpus in part of the bibliometric work, in particular limiting the bibliographic coupling map to the top 1000 papers and rendering to identify a small and manageable set of clusters - see Figure 10). Future studies could:

- Draw upon enhanced computing power and classification techniques to analyse the full corpus and derive the analysis from a more comprehensive base. The emergence of these clusters or categories could also be traced over time.
- Explicitly focus on periphery clusters associated with different problem spaces addressed by (different specialisms in) environmental biotechnology, as van de Klippe et al (2023) have done for cardiometabolic and mental health (e.g. this showed mental health research issues related to refugees, domestic violence or imaging techniques). These innovative techniques might illuminate priorities not just for research to overcome environmental challenges, but for upstream approaches (linked to the waste hierarchy) towards mitigating the social and technological determinants of these challenges.

- Use machine-learning techniques to track topics of interest not captured with previous classification techniques, and/or use semantic-based (instead of citation-based) classification methods. Whereas citation-based clustering methods tend to capture scientific dynamics, semantic methods (specially with machine learning) could be used to track topics from the perspective of problem or usage.

Much of the discussion in this project focussed on the supply side - what (the discipline of) environmental biotechnology can offer, rather than what society demands. Further studies could investigate the extent to which environmental biotechnology investments and innovation have prioritised, for example, management of mining wastes in Peru/Colombia or problems of urbanisation in Chinese/ Indian megacities, in similar ways to earlier investigations that have explored priorities associated with rice agriculture (Ciarli and Ràfols 2019) or neglected diseases (Arza and Colonna 2021).

Examination of intellectual property and funding trends

Whilst data on patents and grants is available, the current project did not provide sufficient time for formal analysis of these. Based on the search term used for the current corpus, we could use the same database (Dimensions) over the same time period (1973-2022) to:

- Examine trends in patenting. Further work could adopt intellectual property as a focus and select databases and search terms to optimise results in this area.
- Examine trends in public sector research funding in the UK and elsewhere, in order to provide a fuller picture of the international landscape of investment in “environmental biotechnology”.
- Again, a focus on funding would need to develop semantic-based classification techniques, as outlined above.

We could also investigate patenting or funding using an expanded corpus/ expanded search terms that integrate wider environmental applications of emerging biotechnologies (reflecting the metamorphosis of the field described above).

Further exploration of the links with synthetic and engineering biology

This project was necessarily limited in scope, and missed a number of emerging areas that might be (increasingly) considered as falling within the wider remit of “environmental biotechnology”. These include, but are not limited to:

- Environmental DNA (expansion of genetic monitoring techniques from controlled conditions to the wider environment)
- Genetic technologies in biodiversity conservation (Redford and Adams 2021)
- The prospect of ecological biotechnology (suggested by a participant at the EBNet workshop, November 4th 2024)

A more structured approach to examining the intersection between established environmental biotechnologies (the current study) and emerging areas of synthetic and engineering biology would require the development of an expanded corpus. This would open up further opportunities to discuss interdisciplinarity (Porter and Ràfols 2009) or patterns of emergence and diffusion (Leydesdorff and Ràfols 2011).

Considering Risks and Benefits in the face of Uncertainty and Ignorance

Potential applications in the fourth generation of environmental biotechnology come with risks, benefits and considerations of uncertainty and ignorance (Stirling 1999). Future studies could:

- Examine the extent to which current research priorities and advisory mechanisms (e.g. ACRE) are fit-for-purpose in the face of emerging applications.
- Pilot and experiment with methods for integrating risk and benefit assessment in the governance of emerging environmental biotechnologies.
- Support processes of reflection amongst the environmental biotechnology community to clarify notions of "sustainability", and consider how to avoid hype in the face of funding pressures.
- Investigate how different sites of application (e.g. the 'intimacy' of water treatment versus the industrial nature of cloistered bioreactors for waste processing) interact with public views towards risks and benefits.

Greater integration of the current work to studies of policy and regulation

Whilst beginning to engage with discussions around regulation, the current project has not allowed dedicated time to policy research (e.g. mapping policies at national or international levels, conducting interviews or workshops with policy-makers). We could do this by:

- Tracing the development of policies in the UK and internationally, both through documentary analysis and elite interviews with policymakers
- Building on studies like Oldham et al (2012) that map the interactions between emerging fields with international environmental frameworks (in this case synthetic biology with the Convention on Biological Diversity)
- A horizon-scan of environmental biotechnological applications of potential relevance/interest to the UK Committee on Climate Change/ Climate Change Act or (at the international level) the Intergovernmental Panel on Climate Change (Working Group III Mitigation of Climate Change)/ UN Framework Convention on Climate Change.

Further exploration of the "futures" of environmental biotechnology, using various more formal approaches to broad and open technology assessment/ foresight (Ely et al 2014) could provide deeper insights into the issues described above. These studies could inform policies for responsible research and innovation at the national (UK) level, and contribute, alongside international efforts (UNCTAD 2024; OECD 2024b), to greater co-ordination across countries and contexts.

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Appendix 1. ANZSRC Standard Research Classification (2020) - Environmental Biotechnology

4103	Environmental biotechnology	
	410301	Biodiscovery
	410302	Biological control
	410303	Bioremediation
	410304	Environmental biotechnology diagnostics (incl. biosensors)
	410305	Environmental marine biotechnology
	410306	Environmental nanotechnology and nanometrology
	410399	Environmental biotechnology not elsewhere classified

Appendix 2. Workshop Programme

“Exploring The Past, Present and Futures of Environmental Biotechnology as a Field”

4 November 2024: Friends House, 173-177 Euston Road London NW1 2BJ

Introduction/ background

The term ‘Environmental Biotechnology’ (EB) is central to EBNet’s activities, but its use has raised some interesting questions. It does not have universal recognition, nor do all users agree on what it encompasses; however, many see a value in the term. The Social Science Working Group of the BBSRC Environmental Biotechnology Network (EBNet) has, since May 2024, been examining the histories, contemporary dynamics and potential futures of the field of environmental biotechnology, drawing on insights from the social sciences, in particular science and technology studies (STS). This event provides the opportunity to learn about and discuss the findings of this research, and to contribute to discussions around the potential futures of environmental biotechnology. The outputs of the workshop will feed into the final report of the EBNet Social Sciences Working Group, to be published later in 2024.

Programme

The Past and Present of Environmental Biotechnology	
10.30	Coffee & Registration
11.00	Introduction & Welcome Jane Calvert (Professor of Science and Technology Studies, University of Edinburgh) (Chair), Sonia Heaven (Emeritus professor, University of Southampton and Lead, EBNet), Adrian Ely (University of Sussex and Co-lead, EBNet Social Sciences Working Group)
11:05 – 11:25	Exploring Environmental Biotechnology: **Exploring the bibliometric landscape of environmental biotechnology as a field** Josie Coburn (Research Fellow, SPRU – Science Policy Research Unit, University of Sussex) & Duncan Moore (Research Assistant, SPRU – Science Policy Research Unit, University of Sussex)
11:25 – 11:40	**Response 1** - Joy Y. Zhang, Professor of Sociology, Founding Director, Centre for Global Science and Epistemic Justice, University of Kent & Engineering Biology Hub for “environmental processing and recovery of metals”. **Response 2** - Andrew Pickford, Professor of Molecular Biophysics, University of Portsmouth & Lead for the Engineering Biology Hub “preventing plastic pollution with engineering biology”.
11:40 – 12:00	Q & A
12:00 – 12:20	COFFEE BREAK

12:20 – 12:40	Exploring Environmental Biotechnology 2: **Contemporary dynamics and debates** Adrian Ely (Reader in Technology and Sustainability, SPRU – Science Policy Research Unit, University of Sussex) & Kyle Parker (Research Fellow, University of Edinburgh)
12:40 – 12:55	**Response 3** - Eleanor Hadley Kershaw, Senior Lecturer in Management, University of Exeter Business School & Co-Investigator "Renewing biodiversity through a people-in-nature approach' (RENEW)" project **Response 4** - Tom Arnot, Senior Lecturer, Department of Chemical Engineering & Co-Director Water Innovation & Research Centre, University of Bath
12:55 - 13:15	Q & A (20 mins)
13:15 – 14:00	LUNCH
Futures of Environmental Biotechnology	
14:00 – 14:10	Introduction to the afternoon sessions Jane Calvert (chair)
14:10 – 14:30	Provocations *5-minute talks without slides, putting forward a specific vision for the future of Environmental Biotechnology* James Chong, Lead Bioinformatics Training for Microbial Environmental Biotechnologies Working Group Meredith Barr, Lecturer in Chemical Engineering, London South Bank University, Lead: EBNet Biochar Working Group Tom Curtis, Professor of Environmental Engineering, Newcastle University Pat Thomas, Award-winning campaigner, journalist and author, Founding Director of Beyond GM and A Bigger Conversation
14:30	World Café (workshop) To include a total of 4 rounds of circulation, with 15 minutes per round. Dimensions/topics for discussion (see guidance for further details): - Molecular/ genetic (mechanistic) engineering vs community (system) engineering approaches - Integration across digital, biological and engineering frontiers: opportunities and risks - The changing role of the private sector and intellectual property in a traditionally "public good" field - Environmental Biotechnology: Prevention and/or cure? The role of regulation to drive types of biotechnology and other solutions

14:30 – 15.00	**Rounds 1 and 2** Discussion on above topics
15:00 – 15:10	**Plenary** 2 minutes from each of the 4 tables
15:10 – 15:30	COFFEE BREAK
15:30 – 16:00	**World Café (workshop): Rounds 3 and 4** Discussion on above topics as per Rounds 1 and 2
16:00 – 16:10	**Plenary 2** 2 minutes from each of the 4 tables
16:10 – 16:30	**Plenary discussion**
16:30	Feedback & closing reflections: - Susan Molyneux Hodgson (Professor of Sociology, Associate PVC for Research and Impact for the Faculty of Humanities, Arts and Social Sciences (HASS), University of Exeter) - Sonia Heaven (Emeritus Professor, University of Southampton and PI, EBNet) - EBSS WG Team
17:00	Close

The EBNet Social Science Working Group (EBSS WG) are Adrian Ely, Josie Coburn and Duncan Moore (University of Sussex), Jane Calvert, Rob Smith and Kyle Parker (University of Edinburgh) and Ismael Rafols (CWTS in the Netherlands).

For further information on this event, please contact EBNet@EBNet.ac.uk

Appendix 3. Summary Notes from Workshop Discussions

Tables in the World Cafe at the 4th November workshop discussed five topics. Four of these were provided in advance (with explanations - as underlined below), whilst the fifth was added on the day, arising from the morning's discussions. Brief (and necessarily limited) summaries from each of the tables are provided below, as reported by EBSS WG members.

Table #1. Molecular/ genetic (mechanistic) engineering versus community (system) engineering approaches (e.g. future trajectories may emphasise interventions at the genetic level of individual species or across microbial communities, each with associated societal implications)

Summary notes by Jane Calvert

Not molecular *versus* community engineering

When talking about the future of environmental biotechnology in the terms laid out in the heading above, a clear point that emerged was that "versus" was not the right word. Both genetic engineering and community engineering approaches were seen to be important, and which was adopted would depend on the context, which might include the challenge being addressed, the perceived urgency of the problem, and the environment in which the technology was being introduced.

The limitations of genetic engineering

Genetic engineering was seen as being useful in some circumstances, for example when a temporary fix was required. However, there were some reservations about these kinds of approaches as oversimplifying complex systems and overestimating the extent to which they could be controlled from the bottom up. The synthetic/engineering biology community was seen to have a lack of understanding of the difficulties of employing microbes that mutate in an environment that changes over time. It was also pointed out that the tools are simply not available to engineer many of the organisms used in environmental biotechnology, which are often not model organisms.

It depends on the context

The point was also made that synthetic/engineering biology can be much more resource intensive than approaches widely used in environmental biotechnology, such as biochar for example, which might work better in a low-resource community. This comes back to the point that the context is all-important in deciding which approach to adopt, and this includes not only the environmental, but also the economic, social and geopolitical context. Participants pointed out that skills in understanding these broader issues were often missing from the training of those who go on to work in environmental biotechnology.

Environmental biotechnology is concerned with communities/systems

Finally, the emphasis in environmental biotechnology on communities and systems rather than single organisms was stressed. This comes with its own challenges – for example, it can be difficult to define the boundaries of a system, and it takes a great deal of research to understand complex microbial communities. To add a further twist, it is possible to apply genetic engineering approaches to the community level, further complicating attempts to distinguish between the two approaches.

Table #2. Integration across digital, biological and engineering frontiers: opportunities and risks (e.g. there will be things to say about using machine learning to design organisms, more generally there are interactions between biology and engineering of systems – a gap but also excitement and possible opportunities)

Summary notes by Kyle Parker

Transferability between disciplines

- Opportunity: Differences in emphasis and understanding (or weighting) of various terms or variables can be an opportunity for inter-community / interdisciplinary learning, due to helpful reframing or unconventional thinking about common issues.
- Risk: Language & terminology – and indeed metaphors – can have different meanings across disciplines; there is an agreed need for a shared lexicon for important concepts, or at least an ingrained recognition that common terms may have different meanings (or importance).
- Risk: different fields or disciplines may have very different focuses, and hence collect different kinds (or amounts) of data. Collaboration may be hampered if it requires the sharing of data that may not exist (because not relevant to a particular discipline).
- Risk: biological data were described as “broad but shallow” i.e. relatively few data points across a relatively large number of samples; this may pose problems for AI and machine learning applications, which rely on large data sets.
- Risk: The complexity of biological systems and a tendency (or need) for hyper-specialisation may pose challenges for generalisation or translation of results to other disciplines (discussant referred to the biological diversity of one field site, which might differ completely from a site only a short distance away).
    - Risk: the absence of standardised models of reporting on microbiome and environmental data could pose challenges for building useful computational models (and collecting adequate data for same).
- Risk: technological progress – especially in AI and computing – is relatively fast compared to the speed at which biologists and engineers can build datasets and refine models; new AI/machine learning analytical tools may develop too quickly / require more or new kinds of data, faster than scientists can provide them.

Collaboration & cultural differences

- Opportunity & Risk: Regardless of fields and labels, scientific enquiry (and especially collaborative projects) is a social practice: maintaining strong relationships and building social capital are essential criteria for success.
- Opportunity & Risk: whomever leads a collaborative project often sets the framing of the problem, and its potential solutions. Collaborators must be mindful of power and relationship dynamics, and care must be taken to ensure that all disciplinary contributions are valued and seen as equal partners. (Emphasis was made on the need for adequate funding for social scientific contributions, which discussants felt are often overlooked in science/engineering heavy projects.)

- Risk: It is vital to have clear understandings of the reasons for collaboration, in order to guard against ‘hype-driven’ or ‘buzz-word chasing’ partnerships that lack a clear goal or reasonable expectation of value or success.
  - Risk: even in cases where a fruitful collaboration is likely, there must be clear communication between teams to understand everyone’s motivations, and manage expectations. This is especially important for inter-disciplinary (or industrial) collaborations, where success criteria, timelines, and risk tolerance may vary greatly.
- Risk: In addition to the scientific/technical work, real time and effort must be devoted to maintaining social relations between teams: “it’s not just about common language and goals, but practices and care and time”.

Regulatory and governance barriers

- Risk: Complex regulatory frameworks in any of the mentioned fields (AI, life sciences, etc.) means that collaboration between fields is potentially even more challenging: the difficulty of trying to adhere to multiple (complex) sets of regulation.
- Risk: combining powerful (invasive?) biological technologies such as biosensors, with large scale or widespread IT tools (Internet-of-Things or machine learning) presents serious data protection and/or privacy issues in unintended/unexpected places or scenarios.
- Risk: different fields have different ideas of / tolerance for / likelihood of ‘risk’: difficult to integrate these divergences; more conservative approaches could hamper the progress of less precautionary fields.
- Risk: how to do comprehensive ‘risk assessments’ across a collaborative project? Likely to be different understandings of the term (and the concept) ‘risk’.

Table #3. The changing role of the private sector and intellectual property in a traditionally “public good” field (e.g. emerging environmental biotechnologies may be more amenable to patenting, which could act as a barrier to their widespread use)

Summary notes by Duncan Moore

The fundamentals of the question

- Many individuals declined to define the public benefit, presume the public’s view on the issue or to what extent it was essential.
- Others questioned whether these roles are changing, or whether the confines of the question were too narrow by not referring to regulation in general.
- There was some discussion on volumes and margins in environmental biotechnology - most areas within it seen as having low profit margins.
- Another question posed was whether public benefit interferes with itself?
  - Public benefit infrastructure with set lifespans can hinder future development - an example given is of councils refusing food waste recycling where incompatible with existing infrastructure.
  - Direct positive effects may stimulate indirect negative effects - it was posed (as a devil’s advocate) that anaerobic digestion technology could incentivise intensive agriculture.

Perceptions of industry by academia and vice-versa

- Some perceived industry as overly conservative when funding academic research - leading to low margins and returns for industry, and less interesting projects and less well-trained students for academia.
- Some also saw industry as (sometimes rationally) uninterested in innovation, with big business often buying and killing innovative SMEs.
- Another perception was that industry is bound to the idea that a big return requires a big investment. Participants noted risky small investments can also yield big rewards.
- SMEs were generally seen as different in character to big business due to their ability to cultivate longer-term relationships between academics and people.
- Participants also noted that public and private can be blurred and how profit is shared is more open to valid criticism than the concept of for-profit.
- Knowledge exchange roles were noted as being very different between industry and academia, with these differences rarely being outlined and understood, often hindering progress.
- Differences in research culture/institutional pressures between industry and academia were noted - industry research kinetics were seen as more “step-wise” and academia’s more “smooth”. Academia was said to have pressure toward interesting but not necessarily immediately impactful research, whilst it was implied that industry has the opposite pressure.

IP and the public benefit - in opposition?

- IP and the public benefit are not necessarily a dichotomy - IP can drive research, add value to low economic value fields and sometimes gating off research with IP may be the lesser of two evils.
- Cas9 patenting was given as an example where IP was both a barrier and an incentive to innovate, as alternatives developed.
- IP can also be a form of transparency – it is possible to be more secretive by not patenting and patented products can be licensed in the medium-term. IP protection is also a prerequisite for copyleft, allowing others to use the knowledge.
- It was noted that open licensing may not require downstream users to follow suit (BioBricks was given as an example) and cheap licensing deals may allow licensees to edit the technology and license it out more expensively.
- Different groups had different starting points on whether patents are a transparency mechanism or just a gating mechanism.
- Participants noted that UKRI research is publicly funded but that the public have no say on whether research is open or IP protected.
- Some areas seemed to be considered better suited to IP protection, others for purely public benefit applications (e.g. valorisation vs bioremediation).
- This idea was extended into a broader idea of whether some things, namely public infrastructure, should be excluded from the private sector altogether.
- The idea that IP has some broader problems that are problematic arose – e.g. GMO issues of “control the genome, control the market” is fundamentally an issue with how IP works

The bounds of IP in practice

- Participants noted that some things can be too fundamental to have IP protection, there was talk of “bells and whistles” being necessary.
- This can act as a disincentive e.g. it’s easier to IP protect CO2 cleanup in a closed system than in the real world.
- Grey areas also exist in IP - freebooted Cas9 is common in biotech, with firms only faced with a bill when releasing a product. There are also issues when licensed patents are revoked.
- The requirement to actively protect IP favours “big fish” as costs can be prohibitive for universities and SMEs. In addition, IP has no inherent value, with most patents financially worthless in practice.
- This is cited as one reason why universities are ill-placed to monetise IP, alongside their risk-averse nature. Value is lost by poor stewardship, and scepticism that universities should even have a share in researchers’ IP was expressed. It was noted that the UK does well monetising software, potentially for this reason.
- Different jurisdictions of IP can be relevant - UK researchers often patent in the US where it is easier to patent, to the UK’s detriment.

Table #4. Environmental Biotechnology: Prevention and/or cure? The role of regulation to drive types of biotechnology and other solutions (e.g. government policy can in some cases negate the need for environmental biotechnology by reducing waste or pollution at source. In others, it can support biotechnological approaches to recycling or management of waste streams. How do we balance these approaches?)

Summary notes by Adrian Ely

The waste hierarchy – refuse, reduce, re-use, re-purpose, re-cycle – should be a guide for industrial processes and also environmental biotechnology, as it is in other sectors. Overall, environmental biotechnology should be used when prior efforts to reduce environmental harms have been exhausted. Policies need to be informed by geographically relevant sector- and case-specific data that goes beyond risk to incorporate life cycle/ multi-criteria analysis and democratic deliberation. Conversations at the table explored various related perspectives:

“There is no waste” - under certain views of the circular economy, all waste streams may be seen as inputs to other industrial processes. However, there are limitations of this view with regard to energy use (second law of thermodynamics) and residues (recycling still produces harmful byproducts). Policies for a circular economy need to address these limitations through regulation (making products and processes low waste, low risk or recyclable-by-design), rather than focussing on the “end of pipe” recycling of wastes. An example would be the use of environmental biotechnology to process oil spills – this has in recent years become less common as stringent regulations reduce the risk of spills.

“Categorising waste” – policies in the UK are currently muddled or ambiguous because they categorise materials differently according to context. Regulations characterise waste (or resources) via different categories, depending on the way it is “disposed of” and valorised e.g. farms are allowed to release more pollution than water companies, humans release (pharmaceutical) pollution through going to the toilet (currently difficult to remove from wastewater), whilst pharmaceutical firms can’t do that. Improvements in categorisation and quality could lead to better environmental outcomes e.g. only 5% of manures go to anaerobic digestion - manure can be considered waste, but food should not be. The quality of waste e.g. broken glass in compost was also highlighted as a challenge. Overlapping regulatory frameworks also make policies incoherent e.g. renewable heat incentive (RHI) and renewable transport fuels obligation (RTFO). Waste/ byproduct/ resource boundaries need to be reconsidered as technology evolves.

"Break glass in case of emergency" - we need to distinguish between decisions around legacy waste and pollution (which absolutely needs to be dealt with) and decisions to deploy environmental biotechnology over the long term in a way that allows continued pollution and waste production. But is it reasonable to expect that technologies won't be used routinely, once they have been developed? Policies around environmental biotechnology need to consider scenarios where "emergency" applications (e.g. those to address bioweapons or contamination events) become routine.

"Lock-in or transition" - the tendency of technology (not just environmental biotechnology) to re-purpose or process waste and pollution can – especially where the products of those processes are high in value – create a market for the waste as a resource. This can build momentum for or lock in polluting activities, even if these feed into circular economies. It can also divert important resources away from human needs (e.g. food for biogas or fuel, rather than for eating). This is particularly worrying when environmental biotechnology is used to enable scale-up, meaning that the amount of waste/ pollution grows. Environmental biotechnologies (and other waste management processes) need to ask themselves "am I locking in the production of waste"? Technologies for waste valorisation should not be used for greenwashing.

"Perverse incentives" carbon markets, taxes and other incentives may be misaligned with social, ecological and other environmental outcomes. In addition, they have impacts beyond their geographies particularly in resource-poor contexts, for example EU CBAM disadvantaging developing countries. These policies also create opportunities for related technologies – if carbon dioxide is coming from manufacturing, then used by diatoms/ algae as a factory in CO_2 removal, is it environmental biotechnology? Bans on particular products or processes can also lead to the adoption of even worse alternatives.

"Context matters" - Context is important and environmental biotechnology needs to consider potential future use contexts. The UN estimates that globally, 80% of wastewater is released untreated. Capacity and politics around implementing regulations differ greatly in different countries, and power plays an important role. Large companies may be successful in reducing the regulatory burden, rather than responding to policy through innovation. Lobbying by technology communities (e.g. engineering biology) mobilises scarce research resources over many years without necessarily delivering on its promises.

"Informing better policy" – policy and regulation needs to be well-designed in order to drive innovation to reduce waste and pollution, whilst funding should support research and pilot testing. Beyond regulatory design, there are considerations around compliance, accountability and enforcement. Most participants thought that current UK policies could be improved. One participant suggested legislating for RRI (responsible research and innovation), although it is unclear how this articulates with existing law. "Risk-based regulation" (with risks of pollutants including environmental, public health and ecosystem-level) is insufficiently attuned to different options. We need more sophisticated life cycle analysis, multi-criteria analysis and agile regulation that is technology-neutral but drives different types of innovation that are suitable for specific contexts. STEM participants said that we need more (social science) research on these kinds of questions.

All statistics referred to above were raised in discussion and noted by participants, but have not been checked by the authors. Likewise, the authors do not necessarily share the perspectives discussed in break-out groups.

Table #5. “The Doughnut Question” - Is it important for this community* to identify what brings the field of environmental biotechnology together?

* = the people gathered now, in this room.

Summary mind map by Josie Coburn

This question was posed during the workshop in response to the bibliographic coupling map of environmental biotechnology publications (Figure 11). The map suggested that according to the corpus of environmental biotechnology publications there are 5 relatively distinct areas within the field that do not strongly build on the same core knowledge, i.e. that the map of the field looks a bit like a doughnut. This possible lack of centre prompted workshop participants to reflect on what (if anything) brings the field of environmental biotechnology together.

The mind map in Figure A1 illustrates the main conversations that took place at this table:

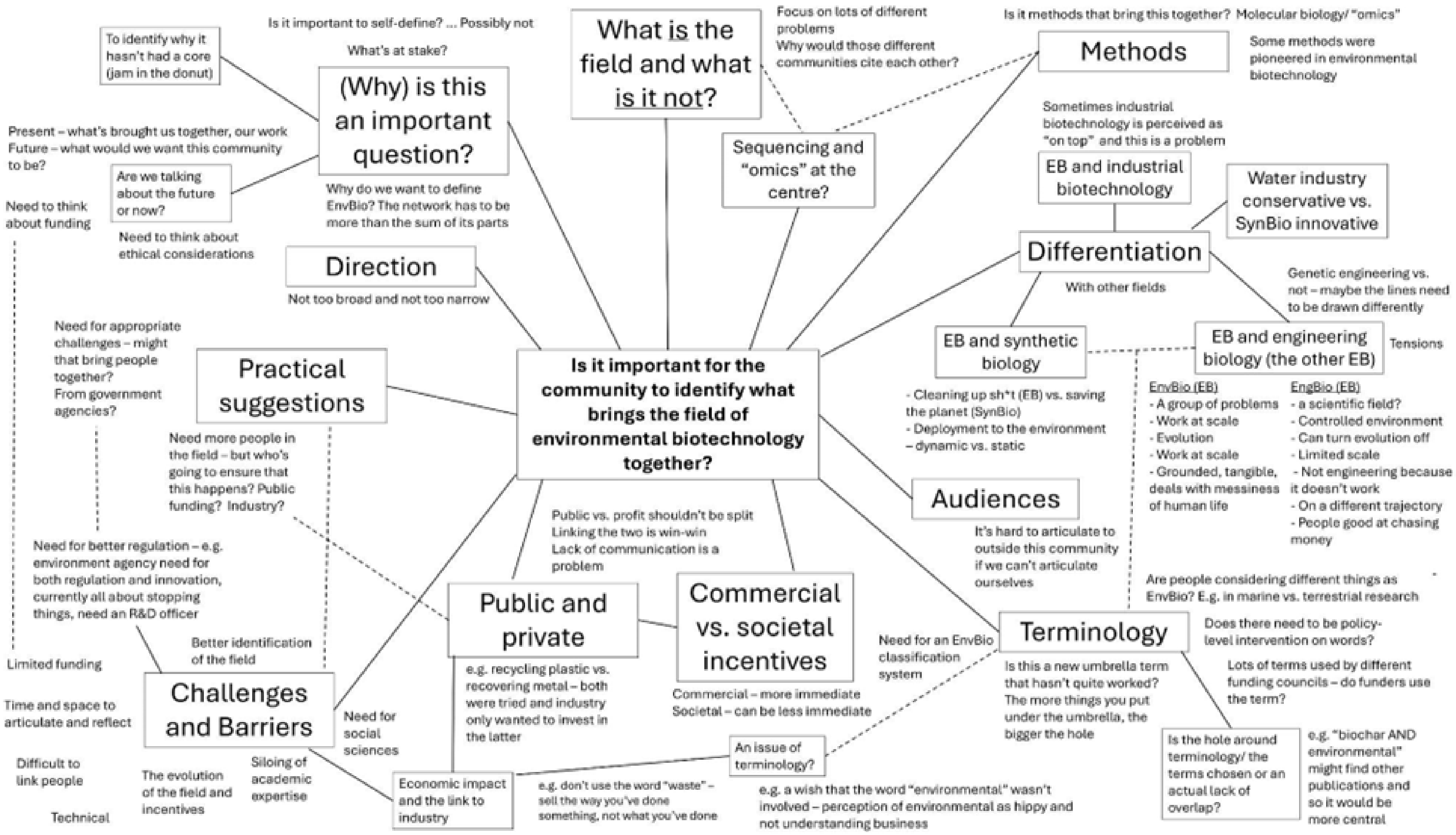

Figure A1 Mind map of discussions at Table #5

(Why) is this an important question? - Participants questioned whether it is important to self-define or not, and highlighted that it depends on what is at stake. This could be an important question to identify why there hasn't been a core of environmental biotechnology. It could be important in the present to identify the work that brings people together, and in the future for thinking about funding structures.

Direction - The direction of the field needs to be not too broad and not too narrow.

What is the field and what is it not? Participants suggested that the field of environmental biotechnology focuses on many different problems, and posed the question - why would these different communities cite each other? There was also a rich discussion about differentiation between environmental biotechnology and other fields, such as engineering biology and industrial biotechnology; and whether methods such as sequencing and "omics" might be what brings the field together.

Terminology- in related discussions, workshop participants questioned the extent to which there might be an issue of terminology, i.e. is the apparent lack of centre of the field related to the use of terminology or is there really a lack of overlap between different areas?

Relationships between the public and private sectors, and between commercial and societal incentives were highlighted as being part of what brings the field together (or not).

The challenges and barriers faced by the field, such as limited funding, a need for better regulation, siloing of academic expertise, etc. were also highlighted; as well as practical suggestions for how to solve some of these challenges, such as government agencies defining appropriate challenges to work on.