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What Is Environmental Biotechnology? Although Widely Applied, a Clear Definition of the Term Is Still Needed

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Abstract

The term Environmental Biotechnology is widely used, but lacks a universally accepted definition, with varying interpretations across disciplines and sectors leading to challenges in funding, policy formulation, and interdisciplinary collaboration. Through a literature review and engagement activities, this study examines existing definitions, identifies key areas of divergence, and explores pathways toward a more cohesive understanding. Findings reveal a spectrum of valid interpretations, often shaped by specific contexts, with researchers generally recognising a shared conceptual framework within their own subfields but encountering ambiguities across subject boundaries. Common points of difference include whether Environmental Biotechnology is restricted to microorganisms or encompasses other biological systems. Some understandings reflect sector-specific needs, contributing to fragmentation, though a broader approach could strengthen the field's identity by providing a unifying framework, mapping overlaps with related fields such as Industrial Biotechnology. A working definition is proposed for Environmental Biotechnology as the use of biologically mediated systems for environmental protection and bioremediation, incorporating resource recovery and bioenergy production where these enhance system sustainability. Importantly, it was recognised that any definition must remain adaptable, reflecting the evolving nature of both the science and its applications.

Keywords: environmental biotechnology; environmental technology; definition; unifying framework; bioeconomy

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1. Introduction

Across the world, many governments are increasingly aware of the need to accelerate the transition to a more sustainable global economy [1,2], and are seeking to identify pathways to, and requirements for, renewable and bio-based industrial systems [3]. Solutions that are rooted in environmental biotechnology have a central role to play in this transition [4], and efforts are already being made to unlock their potential. This is reflected in some significant investments in research and technology translation to replace dependence on fossil resources and the use of environmentally damaging technologies [5–7].

One example of this in the United Kingdom (UK) is the Environmental Biotechnology Network (EBNet) [8], one of six Phase II Networks in Industrial Biotechnology and Bioenergy (NIBBs) which were set up in 2019 with support from the UK's Biotechnology and Biological Sciences Research Council (BBSRC) and the Engineering and Physical Sciences (EPSRC) [9]. These NIBBs were followed by a further investment of around GBP 100 million in six Engineering Biology Hubs [10,11], including the Environmental Biotechnology Innovation Centre (EBIC) [12]. EBNet was established to represent a community of academics and industry practitioners, focusing on microbial systems for environmental protection, bioremediation and resource recovery. Its strategic aim is to bring together natural and social scientists and engineers, to move discovery science towards practical application. Since its creation in 2019, EBNet has grown into a network of over 1300 members from academia, industry, the public sector and non-governmental agencies, from the UK and elsewhere. The Network's activities also contributed to shaping the direction of EBIC as a hub for the development of innovative environmental solutions based on environmental biotechnology.

The term Environmental Biotechnology is central to EBNet's activities, but its use has raised some interesting questions across the life of the Network and its successors. Soon after EBNet began, it became apparent firstly that the public, and many others not directly involved in this field, had little or no idea what the term meant; and secondly, that there were differences in understanding of the Network's remit and of the areas that constitute Environmental Biotechnology, even between EBNet's academic coordinators.

On the other hand, there appear to be clear advantages to having a term of this type. Raising awareness of the critical contribution of biology-based engineering solutions to a more sustainable economy, in particular a bioeconomy that responsibly deploys biogenic resources and biological processes in harmony with natural ecosystems [13], is one of these benefits. The term can also help create and strengthen links between different aspects of the field as a way to promote cross-fertilisation of ideas and the rapid uptake of scientific and technological advances. Another important contribution is the re-branding of areas like wastewater treatment and waste management, which are sometimes seen as old-fashioned and 'dirty', to convey the sheer intellectual and professional excitement of creating practical applications in societally important areas of science focused on combining environmental benefits and public welfare.

Based on these considerations, a range of reviews and other activities was initiated to explore existing understanding and definitions of Environmental Biotechnology, and to address some of the issues identified in the process. This paper presents and discusses the results of these actions and formulates some recommendations on promotion and use of the term.

2. Materials and Methods

2.1. Overall Approach of the Study

To explore how the term Environmental Biotechnology is used and understood in different contexts and by different actors, a mixed methods approach has been applied. A literature review was complemented by a number of activities to gather additional evidence from practice and engage with different communities. The findings collected through these activities were considered in a mini-workshop held as part of an EBNet management team meeting, with the aim of discussing the information gained and developing a working definition for the term Environmental Biotechnology (for details, see Section 4).

2.2. Literature Searches

A literature search was carried out on the Web of Science (WoS) database (Core Collection, version of 30 September 2024) with 'environmental biotechnology' as the search term, from the earliest available data in 1970 to 30 September 2024. The search used the 'All Fields' criterion, and the resulting set of records was also examined for cases where the search term appeared in the 'Title', 'Abstract' or 'Author Keywords' fields, corresponding to a 'Topic' search in Web of Science. A further search was carried out for the same date range using the terms 'grey biotechnology' and/or 'gray biotechnology' (the latter corresponding to American English usage) and the 'All Fields' criterion. These literature searches were supplemented by general non-exhaustive searches on Google Scholar and Google for the same three terms.

2.3. Further Activities to Gather Information on the Term Environmental Biotechnology

In parallel with the literature searches, a range of activities was carried out to gather further information on use and understanding of the term Environmental Biotechnology, and to address some of the issues identified during this process. These activities included the following:

- Support for a study by EBNet's Social Sciences Working Group;
- A review of abstracts submitted to EBNet's annual Early Career Researcher (ECR) conference;
- A review of funding applications received by EBNet under the lens of identifying differing understandings of what falls into environmental biotechnology;
- Gathering and reviewing statements of ECRs on the topic "I am an Environmental Biotechnologist because…";
- Sponsorship of a short story competition;
- Other activities: production of a set of animated video clips; review of keywords provided by members when they joined EBNet; and coordination of an Environmental Biotechnology Awareness Week.

EBNet operates a number of working groups set up in response to issues identified by the members, and funding and other assistance is made available for working group initiatives. Support was provided for a study by EBNet's Social Sciences Working Group on 'Exploring Environmental Biotechnology as a field', including a bibliometric study, interviews and workshop. The results of these efforts are reported in full elsewhere [14], and are not presented in detail here; but interim and final findings were available to the EBNet management team and participating Network members as part of the current work, and relevant findings are integrated as suitable.

A review of abstracts submitted to EBNet's ECR conference series was conducted to identify subject areas and determine how they aligned with the Network's remit and main themes. Submissions from 6 conference cycles (2019 to 2024) have been evaluated, amounting in total to 351 abstracts.

A similar review was carried out for project funding applications received by EBNet, to explore whether the applicants' understanding of what they expect to be fundable under an environmental biotechnology call was in line with EBNet's main themes. It is part of EBNet's role to select projects for funding related to environmental biotechnology and to distribute the funding. Project proposals submitted in four Proof-of-Concept (PoC) funding calls (106 proposals in total) have been revisited under the lens of whether the applicants' understanding of environmental biotechnology was compatible with EBNet's remit.

Another activity was to gather and review statements from EBNet ECRs and others on the topic "I am an Environmental Biotechnologist because...". At the last two ECR conferences, in 2023 and 2024, those wishing to attend were asked to provide a sentence on the theme 'I am an Environmental biotechnologist because...'. This yielded 141 responses that provide evidence on how ECRs see themselves and their activities as belonging to the sector.

Sponsorship of a short story competition under the Green Stories initiative [15] as a means to gain further insights on public understanding of the term was part of the activities conducted. The Green Stories initiative encourages writers to embed 'green' solutions or visions of a sustainable society in stories that target a wide readership, with the goal of fostering cultural shifts through such stories. The EBNet-sponsored Green Stories competition, under the slogan 'Microbes to the Rescue!', asked for short stories showing microbially mediated Environmental Biotechnology in a positive light, with the twin aims of gauging understanding of the term by one sector of the public and gathering useful material for outreach and dissemination. Entrants were given information including a short description of the subject with possible examples of topics, and a briefing webinar [16]. A surprisingly high number of 161 short stories were submitted to this competition.

EBNet also commissioned a series of short video animations to improve understanding of the term Environmental Biotechnology and raise awareness of the disciplines involved. The first of these was entitled "What is Environmental Biotechnology?" [17]. The Network then held an open competition seeking ideas to illustrate why interactions between microorganisms and the engineered environments they inhabit are central to microbial treatment systems and create fascinating scientific challenges for Environmental Biotechnology as a field. The winning ideas were turned into professionally produced video clips.

The Network coordinated an Environmental Biotechnology Awareness Week (#EnvBiotechAware week) [18] to showcase some of its key outputs and promote the subject area in its totality. Promotion and dissemination of outputs and findings during #EnvBiotechAware week enabled conversations around the theme with the broader public.

Where individual statements are quoted in Section 3, these are anonymised, and consent was obtained from participants for quoting their statements.

3. Results and Discussion

The results of the literature searches are presented in a structured way in a separate section of this work (Section 3.1). The other activities conducted are based on approaches with a more explorative, evidence-seeking characteristic, for which the possibilities to distil relevant findings are rather situation-specific. The observations and results gathered through these activities are outlined (Section 3.2) to illustrate specific aspects based on the evidence collected. Then, based on the results obtained, key implications of the lack of a shared definition are discussed in Section 3.3.

3.1. Environmental Biotechnology in the Literature

3.1.1. Basic Statistics on Use of the Term in the Scientific Literature

A total of 3350 items that included the term Environmental Biotechnology were identified in the 'All Fields' search, and 687 using the 'Topic' fields search. Figure 1a shows the number of publications by year. No publications were found before 1985, when a paper entitled 'Environmental Biotechnology and the Water Industry' appeared in the *Effluent and Water Treatment Journal* [19]. The number of publications per year then shows an upward trend in both cases, though the values for 'All Fields' are affected by individual events: for example, the peak of 613 in 2011 is heavily influenced by 477 proceedings papers from one conference [20] and 56 chapters in one reference book [21], although together these only contribute three items to the 'Topic' fields count.

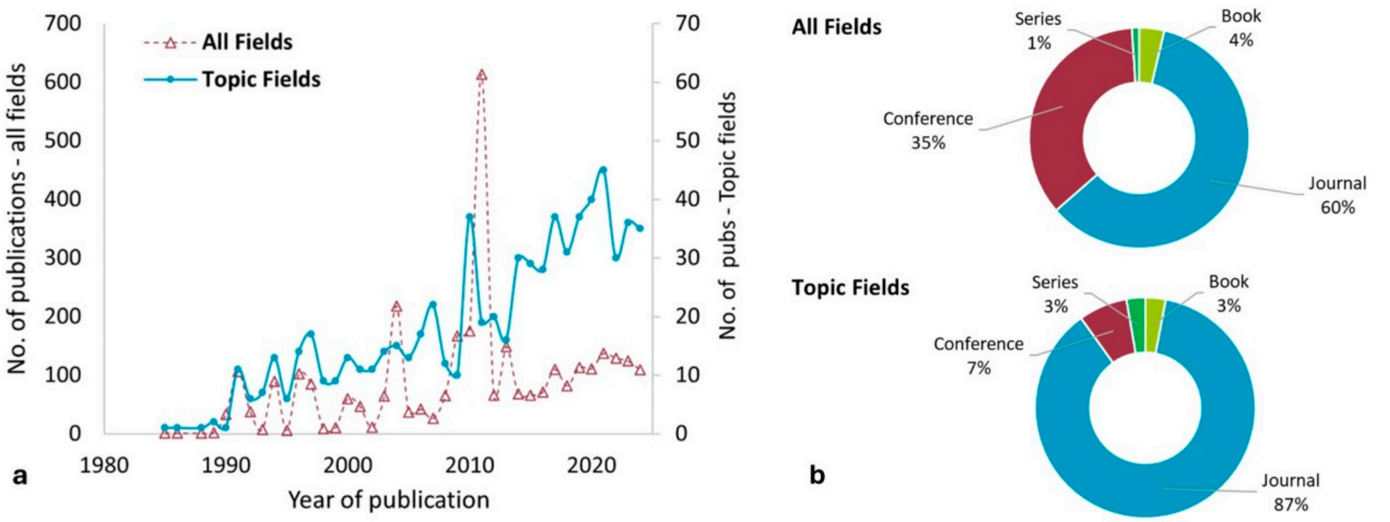

Figure 1. Publications containing the term Environmental Biotechnology (search period 1 January 1970 to 30 September 2024): (**a**) number of publications by year in 'All Fields' search and in 'Topic' search (title, abstract, keywords and keywords plus); (**b**) shares according to publication category.

Of the 3350 items from the 'All Fields' search, 124 were categorised in WoS as 'Books', 2006 as 'Journal' items, 1185 as 'Conference' papers and 35 as coming from the WoS category 'Series'; the relative proportions in each case are shown in Figure 1b. Many of these hits, however, were due to the term appearing in the general 'Source' or 'Conference Title' field of a publication (e.g., as a chapter in a book or a paper in a conference with Environmental Biotechnology in the overall title), without it necessarily occurring in the title, abstract or keywords of the individual publication itself (i.e., the single book chapter or the single conference paper). Overall, 1463 items with the term Environmental Biotechnology, or 43.7% of the total, were findings under 'Source' or 'Conference Title', but in only 33 of these was the term also present in the title, abstract or keywords of the individual publication itself.

The 'Conference Title' count included multiple items from major individual conferences (e.g., the 'European Symposium on Environmental Biotechnology' organised by the European Federation of Biotechnology in Ostend, 25–28 April 2004, with 212 entries; and the 'International Conference on Environmental Biotechnology and Materials Engineering' at Harbin University, 26–28 March 2011 with 477 entries); from conference series (e.g., three international symposia on Gas, Oil, and Environmental Biotechnology organised by the USA's Institute of Gas Technology in 1990–1992, with 100 entries in total); and from a variety of events coordinated by the International Society for Environmental Biotechnology (ISEB) from 1994 onwards [22], accounting for 271 entries in total. The 'Conference Title' count also omitted ISEB events where the organisation name was hyphenated and did not appear elsewhere in the event title (e.g., 6th and 7th Symposia of the 'International-Society-for-Environmental-Biotechnology' in 2002 and 2004, with 45 entries). Items where the term Environmental Biotechnology appeared only in the 'Source' count tended to be book chapters, with one key reference containing 49 examples of this type out of a total of 56 [21].

A total of 1389 items included the term Environmental Biotechnology in the sections concerned with funding attribution (Funding Organisation, Funder Name or Funding Text). Of these, 1381 did not use the term in the title, abstract or keywords. Small differences in attribution wording and format prevented accurate quantification of different funding sources, but a number of key programmes and institutions could be identified. Examples of the former included the NSFC-EU Environmental Biotechnology Joint Program, and the Centre for Environmental Biotechnology Project of the European Regional Development Fund (ERDF); while the latter included the Key Laboratory of Environmental Biotechnology, Chinese Academy of Sciences, and the Environmental Biotechnology National Core Research Center in Korea.

Many literature reviews direct their attention to publications where the search term or terms appear in the title, abstract and/or keywords, since searching all fields is likely to bring less relevant items into the dataset. The current survey found 687 items with the term Environmental Biotechnology in the 'Title', 'Abstract' and/or 'Author Keywords' categories, and a further 9 items where it appeared in 'Keywords Plus'. The 'Keywords Plus' category is generated by algorithms based on commonly occurring terms in the title, keyword and cited references of a publication [23]. The small number of 'Keywords Plus' found is potentially of interest with regard to use and understanding of the term Environmental Biotechnology, but this aspect was not investigated in more depth in the current work.

Of the 696 items identified from the 'Topic' fields, 21 were categorised by Web of Science as in Books, 606 in Journals, 50 in Conferences and 19 in Series. The Book references came from twelve books, five of which had the term Environmental Biotechnology in the title, while the remaining references were in chapter titles or author keywords. Journal papers consisted of 353 items listed as 'Articles' (including 6 early-access and 17 proceedings papers), 160 as 'Reviews', 73 as 'Editorial Material' and a small number as other formats (1 'Letter', 1 'News' item, 1 'Note' and 3 'Book Reviews'). In some types of study, 'Editorial Materials' are treated separately from other items, as they tend to be about setting a research agenda rather than being unique research contributions in their own right. They may also create 'noise' in the bibliometric analysis, especially where citation numbers are taken into account; but their inclusion can be valuable to expand the basis for research performance analysis [24]. In this case, they were considered quite likely to contain material relevant to definitions of Environmental Biotechnology, and were therefore reviewed with the other categories. It should also be noted that the above categorisations are not necessarily robust or definitive: for example, in several abstracts the work was self-defined as a review, although the item was categorised as an 'Article'. For the purpose of the current work, however, this was not considered a problem, and the original categories were accepted with no attempt at reclassification.

The results of the Web of Science search were further analysed to identify the journals favoured by these authors. The term Environmental Biotechnology appeared in the title, keywords or abstract of publications in 284 journals in total; but only 17 journals had more than 5 uses, including in 'Editorial Materials'. Figure 2a shows the distribution by journal of papers identified in the 'Topic' search for journals with more than 5 relevant publications. The most frequently appearing is 'Current Opinion in Biotechnology', with 39 entries made up of 16 'Review' papers, one 'Meeting Abstract' and 21 'Editorial Materials', with only one 'Article' [25]. The high proportion of 'Editorial Material' reflects this journal's policy of offering editorial overviews in key subject areas, including environmental biotechnology, which provide useful insights on usage and definitions—implied or explicit—for this term.

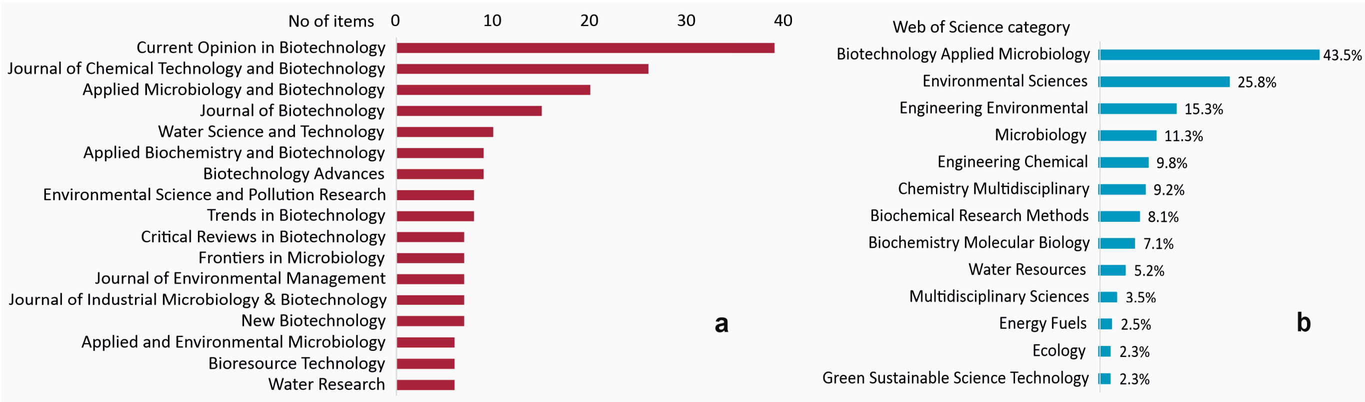

Figure 2. Details of 'Topic' search for Environmental Biotechnology (search period 1 January 1970 to 30 September 2024): (**a**) journal frequency: number of publications by journal for journals with >5 relevant publications; (**b**) allocation of hits by Web of Science to database categories.

Thematically, the 696 hits obtained in the Web of Science 'Topic' search were allocated to 90 out of the total of 254 database categories, confirming the multidisciplinary nature of Environmental Biotechnology. Figure 2b shows only those categories with at least 2% of the total number of allocations (note that one journal, and hence also one item in it, may be allocated to more than one category). This list may be instrumental in deriving associated keywords and identifying the main disciplines concerned, such as microbiology, environmental sciences and environmental engineering, and hence may be of reference value for others in future. It is interesting to note that the Web of Science database does not have a separate category 'Environmental Biotechnology'.

3.1.2. Interpretation of Key Observations from the Literature Search

In total, almost 80% of items identified in the 'All Fields' search, namely 2663 items, did not have the term Environmental Biotechnology in the title, abstract or keywords. The fact that many of these were submitted to books or conferences with Environmental Biotechnology in the title indicates that the authors are comfortable with the term and believe their work belongs in this field. Acknowledgement of support from relevant funding programmes also suggests a shared understanding of the term; and where Environmental Biotechnology forms part of the name of an institution or initiative, it is again likely there is some consensus on its meaning, though not necessarily an identical one in different organisations. It therefore appears that the term effectively functions as an umbrella for thematically related works to facilitate sharing of knowledge between relevant topic areas. This insight is discussed in more depth by Ely et al. [14].

Absence of the term from the title, abstract or keywords suggests, however, that the focus of an item is on more specific elements, e.g., a technical process of interest or a distinct area of application, and it is thus less likely to be concerned with the nature and definition of the overall field. This interpretation was supported both by examination of individual references and by examples from conferences addressing very specific technical aspects of the field, such as the 'Symposium on NMR in Environmental Biotechnology' held at Wageningen, Netherlands on 5 November 1999 (12 items) or the 'Workshop on Photosynthetic Microorganisms in Environmental Biotechnology' in March 2000, in Osaka, Japan (19 items). These items were of less value in the search for explicit definitions of the term, and are therefore not considered in detail in the remainder of this review.

3.1.3. Definitions of Environmental Biotechnology from the Literature Search

A range of publications identified through the literature search, complemented by the searches on Google Scholar and Google (see Section 2), was examined for content relevant to definition of the term Environmental Biotechnology. The following is, of necessity, a brief overview, but attempts to highlight some useful examples, and to identify patterns and points of interest.

Many publications did not contain explicit definition statements or discussions. These items could be broadly grouped into two main types. First, there were items primarily concerned with optimising a specific process or technology, e.g., in waste or wastewater treatment or bioremediation. They therefore tend to contain little or no discussion of the term itself: it is evidently assumed that anyone reading would understand and agree with the implied definition—or, if they do not, that this is not serious and will not lead to confusion, since the reader is certainly interested in the specific topic area of the paper. A second group consisted of items focusing on new tools, techniques or knowledge directly applicable to key areas of Environmental Biotechnology: again, these usually do not define or discuss the term itself. Examples of this type include work on extracellular electron transfer [26,27], the microbial sulphur cycle [28] or whole-cell bioreporters for identifying contaminants [29]. A subcategory of this second group dealt with advances in current capabilities or understanding which might be of relevance in Environmental Biotechnology, but which were often more fundamental, less directly targeted on this area, and also potentially useful in other disciplines and activities. Where the term occurs in the 'Topic' fields or main text, it is often once only, as a brief nod to the subject area (e.g., [30–33]). These references were identified and incorporated into broader analysis of the extent and boundaries of the term/subject area in the main bibliometric study [14], but they were not examined in any further detail for this work.

Where definitions were given, some appeared too broad to be helpful in the demarcation or delineation of a field. For example, "Environmental biotechnology includes the application of biotechnology processes and products to any aspect of the environment" [34] and "Environmental biotechnology can be defined as 'managing microbial communities to provide services to society'" [35]: both offer broad coverage, but could also include biotechnologies such as brewing or production of antibiotics, which are generally considered to lie in other disciplines.

In many cases publications describe what Environmental Biotechnology is intended to achieve, and/or the processes or media where it is commonly applied. A succinct example of this definition-by-explanation is "Environmental biotechnology provides solutions to the problems related to excessive exploitation of resources and the consequent pollution" [36]. Another example, which also touches on the history of the discipline, is as follows: "Environmental biotechnology is concerned with the application of biotechnology as an emerging technology in the context of environmental protection, since rapid industrialization, urbanization and other developments have resulted in a threatened clean environment and depleted natural resources. It is not a new area of interest, because some of the issues of concern are familiar examples of 'old' technologies, such as: composting, wastewater treatment etc." [37]. Other references list a similar but wider range of technologies (e.g., Hesham et al. [38]), with the majority including biological [waste]water treatment and bioremediation of contaminated soil or water. Indirect definitions of this type can also be deduced from chapter titles listed in a book or presented as topics in its introductory material [39–42].

One potentially significant distinction between definitions concerns the biological agents involved. Some references specify microbial processes and products [NB: our italics throughout]: "Environmental biotechnology *utilizes microorganisms* to improve environmental quality. These improvements include preventing the discharge of pollutants to the environment, cleaning up contaminated environments, and generating valuable resources for human society" [43]; "Environmental biotechnology is a system of scientific and engineering knowledge related to the use of *microorganisms and their products* in the prevention of environmental pollution through biotreatment of solid, liquid, and gaseous wastes, bioremediation of polluted environments, and biomonitoring of environment and treatment processes" [44]; and "Environmental biotechnology relies on *microorganisms and their enzymes* to protect, improve, or restore environmental quality" [21]. The same assumption is present, though implicit, in other cases [45–47]. On the other hand, some references specifically mention other organisms such as plants and insects [36,48,49], while others choose a broader definition encompassing any biologically mediated activity. One important example of this, widely quoted by others [50–53], comes from the ISEB website: "The International Society of Environmental Biotechnology... promotes interest in environmental biotechnology and offers the exchange of information regarding 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)" [54].

A sub-aspect of this issue of biological agents is the role of synthetic biology, where this refers to genetic modification (GM) of organisms, components and pathways. In some early references, especially from US authors, the term Environmental Biotechnology is treated as almost synonymous with GM [25,55,56], while others acknowledge the roles of both modified and natural entities, but anticipate greater impact from the former [57–59]. On the other hand, many publications debate the relative capacities of natural versus GM systems [60,61], and, in particular, champion the significance of microbial ecology and microbial communities for this field [62–66].

Perhaps the most significant differences between definitions were related to the scope of the field, in particular the degree to which it specifically addresses the area of environmental protection and remediation or also includes activities focused on resource valorisation, renewable bioenergy and bio-based product generation. Definitions ranged from references where Environmental Biotechnology is captured primarily or exclusively in terms of clean-up and restoration [21,36,67] to those which explicitly include a much wider array of activities [68,69]. This difference can be seen in the definitions already quoted, although some are potentially ambiguous on this point, thanks to the fuzzy quality of conjunctions used in ordinary writing when compared to precise logical operators in legal or mathematical use: for example, the '*and*' in the phrase "*and* generating valuable resources for human society" [43] could be interpreted as logical 'AND', logical 'OR' or even 'and/or'. Other references were more explicit on this relationship between valorisation activities and environmental protection, emphasising the latter's central role in a more sustainable society while also noting the typically low-value nature of its activities: "Environmental Biotechnology needs solutions that are associated with a low budget and cleaner remediation, and which are *connected to* resources and energetic valorization, to be able to *encourage a circular bioeconomy*" [70].

The wider definitions comprised an expanding circle, from adjacent areas to more remote activities. Bioremediation is sometimes used as a near-synonym or alternate for Environmental Biotechnology [36,71], although the former is not always seen as including the proactive treatment of contamination before discharge to the environment, e.g., as in wastewater treatment. Ancillary technologies such as biosensors for environmental monitoring are also a key area [72]. Other commonly referenced topics include green chemistry and agricultural biotechnology, while more specialised uses include construction biotechnology [73] and conservation [74]. Such aspects may be highlighted within a conventional list: "Environmental Biotechnology is defined as a branch of biotechnology that addresses environmental problems, such as *the genetic rescue of a species*..." [75]. Other examples with the potential to attract debate over their status as constitutive elements in Environmental Biotechnology include the gut microbiome [76] and medicinal plants [77]. The literature also includes reports on educational initiatives that emphasise the need to draw together diverse disciplines, while not necessarily defining limits to the subject area [78,79].

Several discussions referred to the origins of the field, while also showing differences in perspective: compare, e.g., "In its early stage, environmental biotechnology *has evolved from chemical engineering*, but later, other disciplines (biochemistry, environmental engineering, environmental microbiology, molecular biology, ecology) also contribute to environmental biotechnology development" [37] with "Environmental Biotechnology *has developed as an off-shoot from sanitary engineering*, and only recently the biological component of the ecosystems had been recognized as relevant when bioremediation strategies must be chosen to solve environmental problems" [80]. The same division appears elsewhere [19,67,81,82], while others see a transition from civil engineering origins towards chemical engineering [83]. Although a minor point, this is intriguing in that it potentially mirrors differing views on the relative importance of clean-up and pollution prevention versus resource management and valorisation as the defining elements in Environmental Biotechnology.

This variety of perspectives has been reported by other authors: "Environmental biotechnology can mean many things. What it means to any particular individual depends very much on their scientific background and also on the context of a particular investigation. The molecular biologist might consider factors such as horizontal gene transfer and delivery of novel pollutant-degrading capabilities to a microbial community as a key component of environmental biotechnology, whereas the microbial ecologist may consider the complexities of microbial community composition and their response to the environment as the cornerstone of the discipline. To some it may mean the exploitation of the global gene pool as a resource for the search and discovery of novel bioactive compounds, and for engineering practitioners it may be any technological process applied for environmental benefit that relies on the activity of the biota present in a particular natural or engineered environment" [84].

3.1.4. Environmental Biotechnology as a Term in Other Definitions

One alternative categorisation for biotechnologies is based on colour [85]. In this system, Environmental Biotechnology is often mapped to grey (or gray) biotechnology; although the suggestion that the latter term is now dominant [86] is not entirely supported by the data. The first reference found was dated 2004, but the term Grey Biotechnology is still relatively rare in scientific journals, with only 7 hits in Web of Science for the specified search period, and 322 in total for Google Scholar. As with Environmental Biotechnology, the term is sometimes used without being defined [87,88]. Some definitions are similar to those used for Environmental Biotechnology: "'Grey' biotechnology covers applications which serve environmental protection" [89]. Others highlight less common aspects, e.g., "Gray Biotechnology is dedicated to environmental applications and focused on the *maintenance of biodiversity* and removal of pollutants using biotechnological approaches" [90]. A general Google search found several similar descriptions that foregrounded biodiversity (e.g., [91–93]). As with Environmental Biotechnology, however, usage was not consistent. Several authors mention four to five colours, sometimes described as the 'rainbow' code [94]; but while some of these were present in most cases, there was no fixed number [88,94,95]. Table 1 presents a more extensive set of colours adopted by some authors.

Table 1. Examples of biotechnology classification by colours (based on Matyushenko et al. [96]).

Colour		Definition by Industrial Area
	Red	Biomedicine, biopharmaceutics, diagnostics
	Yellow	Food biotechnology, nutrition science
	Blue	Aquaculture, coastal and marine biotechnology
	Green	Agricultural biotechnology, bioenergy, biofertilisers, bioremediation, geomicrobiology
	Brown	Arid zone and desert biotechnology
	Black	Bioterrorism, biowarfare, biocrime, anti-crop warfare
	Violet	Patents, publications, inventions, intellectual property rights (legal, ethical and philosophic issues)
	White	Industrial biotechnology
	Gold	Bioinformatics, nanobiotechnologies
	Grey	Environmental (ecological) biotechnology

This categorisation also shows variations, however, with some specific issues for the definition of Grey Biotechnology. One grouping similar to that in Table 1 describes White Biotechnology as 'Gene-based bioindustries' and Grey as 'Classical fermentation and bioprocess technology', while environmental biotechnology is allocated to Green [97]. Allocation of bioremediation to Green rather than Grey Biotechnology, as in [96,97], creates a potentially problematic disjunction, as is also the case for biofuels and biofertilisers, given their significance in anaerobic digestion as a waste treatment process.

Only 89 references in Google Scholar used both Grey (or Gray) Biotechnology and Environmental Biotechnology. The majority of references found used 'Grey' rather than 'Gray', where the latter corresponds to American English usage.

3.1.5. Descriptions of Environmental Biotechnology in Other Sources of Information

General descriptions of environmental biotechnology are also provided by sources from publishers [98] to online encyclopaedias [99] and, increasingly, by artificial intelligence (AI) algorithms in search engine summaries, although all of these often contain a range of possible definitions. 'What is environmental biotechnology?' is also a minor topic on ResearchGate [100], launched August 2023 (five responses). One minor inconsistency noted during the survey was that several companies offer reports on the scale of, and trends in, global markets for Environmental Biotechnology (e.g., [101,102]), without there being a generally accepted definition on the term. When contacted, these companies on request provided general descriptions of the methodologies used to frame environmental biotechnology as a topic of interest. In general, these were based on a list of sectors or applications covered, which was similar to those identified in many of the literature references (e.g., wastewater treatment and bioremediation), supplemented by insights from industry experts and the use of artificial intelligence (AI) tools and algorithms.

3.2. Further Activities to Explore Understanding and Use of the Term

In parallel with the literature searches, EBNet carried out a variety of other activities to gather further evidence on use and understanding of the term Environmental Biotechnology, and to address some of the issues identified in the process. A main undertaking was a study entitled 'Exploring Environmental Biotechnology as a Field', conducted by the Environmental Biotechnology and Social Sciences Working Group. The results of this are reported in full elsewhere [14], and clearly confirm the lack of a common definition or understanding of the term.

A review of abstracts submitted for the Network's annual ECR conference investigated how the abstracts aligned with EBNet's main themes, and with the activities of other NIBBs.

Around 10% of the 351 abstracts assessed were considered technically outside of EBNet's remit, with a further 19% marginal or uncertain based on the information given (see Figure 3a). This included work that did not involve biotechnology (e.g., thermal processes) and/or had no apparent application to environmental protection, but also topics such as remediation by macrophytes. It should be noted that EBNet's remit was deliberately limited to microbially mediated processes, omitting bioremediation by plants and other organisms, in order to limit its already very broad coverage. These borderline submissions may provide further evidence of a lack of consensus on the delineation of the field. Intriguingly, however, the proportion of such submissions rose rather than fell over time, suggesting the event was perhaps attracting ECRs whose research interests, although not directly addressing key issues in Environmental Biotechnology, were related to the field somehow, and who found the conference and the Network a useful home.

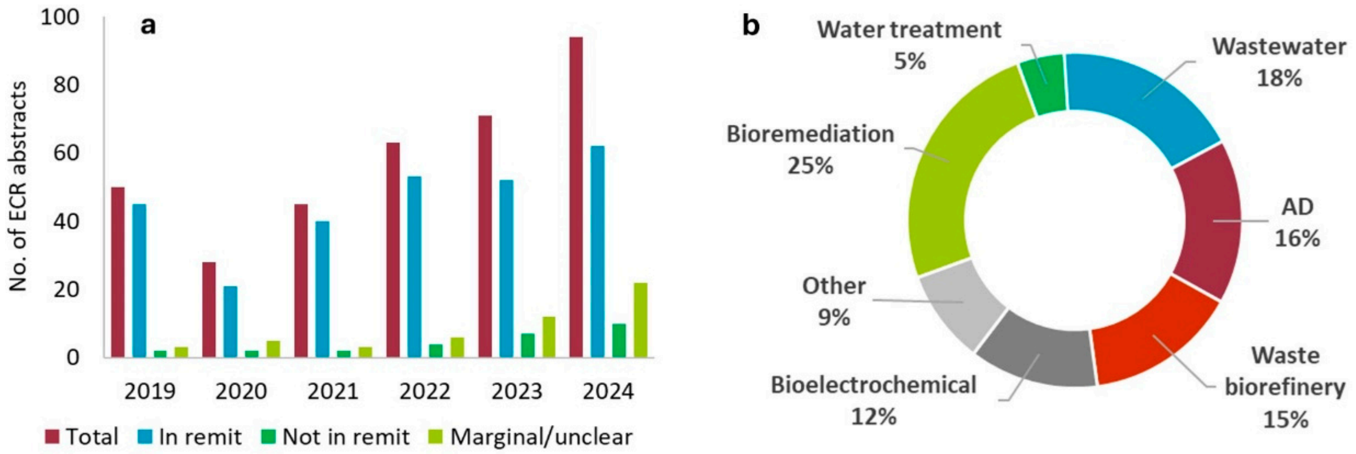

Figure 3. EBNet members' conception of Environmental Biotechnology and of EBNet's remit based on (**a**) EBNet ECR abstracts by year—status with regard to Network remit. (Note: the 2020 and 2021 ECR events took place online under COVID-19 restrictions, with slightly different participation rules, including for abstract submission); (**b**) Proof-of-Concept (PoC) funding applications submitted to EBNet, grouped by main topic area.

A similar review was carried out for the 106 Proof-of-Concept (PoC) funding applications received by EBNet in four funding calls. Four proposals were not eligible for basic formal reasons, while a relatively high number (fourteen) could not be considered due to incompatibility of the topic (eight concerned environmental engineering but lacked biotechnology elements, four lacked a direct environmental aspect, and two concerned macrophyte systems). The remaining 88 bids covered a broad range of topics (Figure 3b), in most cases corresponding closely to the main sectors mentioned in the literature survey, while there was also noticeable interest in bioelectrochemical systems, for applications from sensors to fuel cells; and a variety of topics in the Other category, from bio-coatings for fertilisers to odour-reducing microbial additives designed to reduce textile waste. Applications were first reviewed by independent experts and then passed to an assessment panel with academic and industry participants. Comments made at all stages of the review process reflected similar uncertainties over the definition of the term Environmental Biotechnology to those noted above, viz. "Not a good fit for EBNet—this project reads more like about ecosystem services"; "The process itself is actually physico-chemical rather than biotechnology. But the proposal explains how the idea is directly relevant to transforming anaerobic digestion, which is a key environmental biotechnology"; "The proposal is based on the use of enzymes for environmental remediation, which is within the remit of EBNet (unless we say somewhere that it isn't?) and thus in scope of the call".

An analysis of free-form keywords provided by more than 1000 Network members when they joined EBNet was carried out, to provide a snapshot of self-declared interests. The results form the basis of the world cloud presented as Figure A1 in Appendix A. As expected, words such as biotechnology, microbiology, wastewater, biology, environmental, engineering, and anaerobic digestion appeared frequently, but topics such as biochar, pyrolysis and hydrothermal processing were also mentioned, indicating that this spread of interests occurred across the membership, as well as amongst the ECRs.

At EBNet's last two ECR conferences, those wishing to attend were asked to complete the sentence 'I am an Environmental Biotechnologist because. . .' or to formulate a statement around this sentence. A total of 141 responses were received from 120 participants (some taking part in both conferences), with a further 49 contributions from people who registered but were finally unable to attend. These ranged from brief to lengthy: the very succinct "I am a chemical and environmental engineer" is perhaps another example of the belief in a shared understanding and consensus found in the literature survey. Others focused on saving the planet, or gave detailed descriptions of the excitement of a particular aspect of work (some examples are shown in Figure 4, with others available on the EBNet website [8]). This may hint at a distinction between those individuals primarily self-identifying with the end purpose of their work as the pursuit of environmental benefit, versus others who self-identified with their chosen applied technology. A training event was also organised where nine ECRs made short video clips on the theme of 'I am an Environmental Biotechnologist. . .', with selected examples posted on the EBNet YouTube channel [17]. In both cases, these activities aimed to raise awareness and appreciation of the field.

Figure 4. Examples of EBNet ECR "I am an Environmental Biotechnologist. . ." statements.

A further initiative was to sponsor an open competition under the Green Stories initiative [15,16], inviting authors to submit short stories which unfold plots that are linked to environmental biotechnology. With 161 submissions, the interest was high, suggesting that many authors found the theme and the context appealing. The competition provided some fascinating insights: the most relevant were that, even with the rubric and supporting information, participants often found it difficult to distinguish Environmental

Biotechnology from areas such as medicine; and many could not bring themselves to take a positive view of processes involving microbes. Even amongst the winning entries, five out of twenty-three referenced the unglamorous side of working in Environmental Biotechnology, while two of these specifically depicted people's attitudes changing as they learn more about some aspect of the field. While the group of respondents was highly specific (i.e., the story-writing public), the results provided additional evidence of a widespread lack of understanding of the term, as well as its perceived lack of glamour. Selected stories were published in two anthologies [103,104], supplemented by a report with more detailed discussion of the insights gained [105].

The video animation competition, itself focused on exploring specific interactions between micro-organisms and their engineered environments, yielded a limited number of entries from a rather specialised, mainly academic community. Five specific topics were selected (aerobic granular sludge, anaerobic fermentation, microbubbles in wastewater treatment, microbial ecology and slow sand filtration) and the resulting animations made available on YouTube [17]. In each case, the topic is placed within the context of its environmental benefits. While the ideas submitted under the competition covered a variety of technologies and processes, a common theme was that microbially mediated processes were presented as beneficial enablers for environmental protection.

The #EnvBiotechAware week coordinated by EBNet showcased some of the Network's key outputs, while promoting the subject area in a holistic way [18]. This presented Environmental Biotechnology as a mosaic of individual pieces. Since its inception, the majority of the Network's activities were driven by subsections of its membership interested in specific areas: for example, 13 member-initiated and member-led Working Groups provided numerous specialist webinars, reports, animations and other content [8]. Condensing these accomplishments into one week was an opportunity to draw the community together to appreciate the breadth of research, disciplines, people and challenges addressed. For the public, it provided an accessible way to 'dip in' and gain an overview of what environmental biotechnology means to academics and industrial practitioners. In this way it helped to convey the inclusive role of Environmental Biotechnology as an umbrella term for multiple areas of activity.

3.3. Implications of the Lack of a Shared Definition for the Subject and the Network

The results of the literature survey indicated that there was no single widely agreed definition of the term Environmental Biotechnology or of its remit, and EBNet's further activities created strong evidence to support this. An obvious question is, does this matter? One possible answer is, perhaps not much. This is clearly a vibrant area in terms both of research interest and of market expansion [101]. In the literature and elsewhere, it seems people working in the field are largely comfortable that they share a common understanding and consensus, at least in areas close to their own topics—though the opinions of others in more distant disciplines might cause them mild surprise. There are, however, some potential issues and sources of contention or concern, mainly in the areas of funding and recruitment.

With regard to funding, it is in general more difficult to advocate for anything that lacks a clear definition, or to formulate policy and other interventions to support it. Absence of definitions or discussion can also lead to promising approaches in critical areas being missed or passed over. Research teams in this sector often complain of having proposals rejected because they fall between traditional funding categories, such as biology/engineering. EBNet members reported several cases of such issues during the Network's 6-year operating period. Intersections with neighbouring topics are also affected by the absence of a definition, and this lack of clarity may allow other disciplines to claim ownership of a subject area, especially in a competitive funding climate. The literature contains more- and less-recent examples of this concern that key areas in Environmental Biotechnology are both encroached on and excluded, without adequate intellectual justification [64,106]. This perceived issue is mentioned in EBNet's responses to surveys carried out by the UK government and other bodies to assist in policy formation [107,108], and is also touched on in the main social sciences EBNet study [14].

Even within EBNet, there were examples of funding issues caused by misunderstanding over remit. An obvious yet recurrent case arose from part of the Network's own definition of its strategic aim to bring together a community involved in "...creating and optimising engineered microbial systems for *environmental protection, bioremediation* and *resource recovery*" (Figure 5). When this was written, the authors believed it was clear that the last of the three terms in italics was necessarily dependent on the preceding ones, i.e., resource recovery in the context of environmental protection and/or bioremediation (c.f. the ambiguity noted above in Rittmann and McCarty [43]). That this view was incorrect was demonstrated by lively discussions on this point with external panel members in several funding calls organised by EBNet; and by several disappointed applicants, whose proposals were discouraged or rejected because they concerned, for example, advanced methods for generating value-added bio-products, but neither of the other critical elements. A further potential ambiguity was created by the reference to 'engineered microbial communities', where the first word can be interpreted in different ways, and may inadvertently reference the above-mentioned debates on GM in environmental biotechnology.

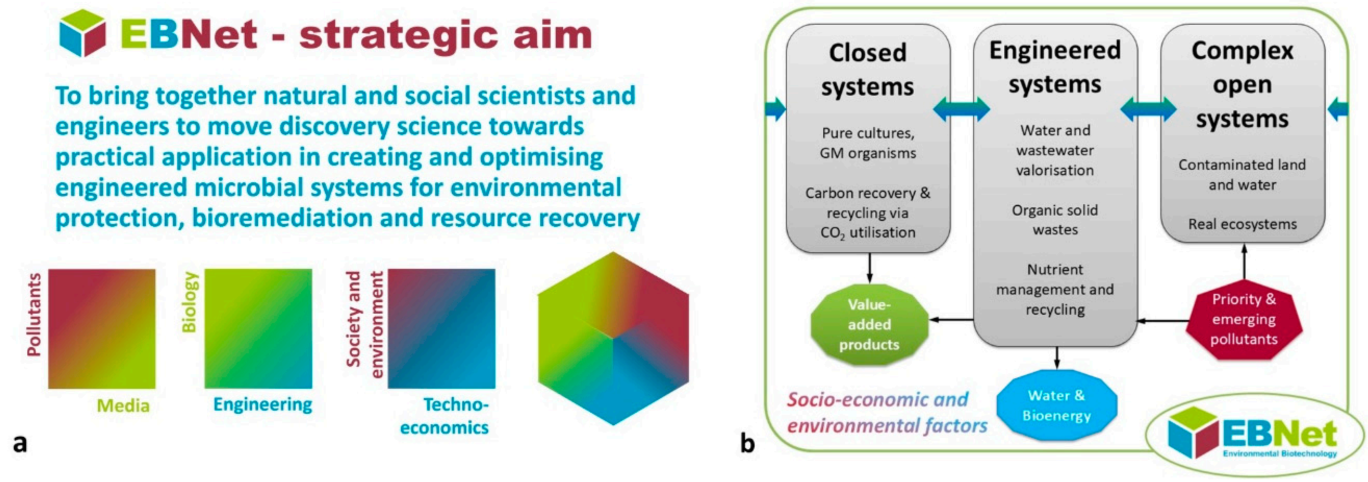

Figure 5. EBNet scope and aim according to Network materials: (**a**) EBNet strategic aim with three main thematic areas that define its operating space; (**b**) schematic illustrating relations between elements within the Network's remit.

Concerning recruitment, obstacles are created by a lack of understanding of the term Environmental Biotechnology, combined with the historically low status of some of its elements. Evidence for this is sometimes qualitative and by assertion, rather than statistically based, but shows a significant history [109–112]. Extracts from one example, which may also suggest a link between low status and low budgets, include the following: "While pharmaceutical biotechnology represents the glamorous end of the market, environmental applications are decidedly more in the Cinderella mould... Cleaning up contamination and dealing rationally with wastes is, of course, in everybody's best interests, but for most people this is simply addressing a problem which they would rather had not existed in the first place... In general such activities are typically funded on a distinctly limited budget and have traditionally been viewed as a necessary inconvenience. This is in no way intended to be disparaging to industry, it simply represents commercial reality” [39]. While there is justifiable debate over the wisdom of taking ‘data’ as the plural of ‘anecdote’, informal views can, nevertheless, provide a revealing snapshot [113,114]. One such example, which illustrates both the widespread uncertainty about what Environmental Biotechnology is, and its perceived lack of glamour as a field, comes from an EBNet Joke Competition, where one winning entry simply asked: “How do you gain admirers at a cocktail party? Say you work in Environmental Biotechnology. How do you lose them? Explain what it is” [115]. Other entries were similar in tone, while EBNet’s director is reported as often quoting her mother’s comment on a move from the water industry to a post in the waste management sector: “Well, dear, I suppose after seven years in sewage, rubbish is a promotion?”. This issue of perceived status and public recognition is especially important when there is strong competition for staff across the broader area of biotechnology. A recent survey by the Chartered Institution of Wastes Management (CIWM), the Environmental Services Association (ESA), Groundwork, Letsrecycle.com and ESS Expo, of around 1500 professionals across the UK environmental services industry, found that 58% agreed there is, or will be, a green skills gap within the sector; while 21% were unsure and only 21% said no [116].

4. Towards Definitions

These attempts to explore the term Environmental Biotechnology took place across the lifetime of EBNet, and the topic was considered at an informal mini-workshop held as part of a Network management team meeting. This included a discussion of some complex or ambiguous examples that might appear to be outside of, or only marginally related to, the Network’s remit, at least until further information is provided. Several were based on real examples from EBNet’s ECR events and funding calls:

- A better tool for gene editing. . . targeted specifically at microbes designed to degrade recalcitrant pollutants?
- An electronic device to measure sludge dewaterability. . . used to explore links between biological and physico-chemical parameters in residues from novel bioprocesses for waste treatment?
- Development of non-clogging membranes. . . tested for use with in situ product recovery from ‘dirty’ mixed-culture microbial fermentations?
- Mapping of potential bioresources for biochar. . . where the proposed application is as a biofilm carrier in wastewater treatment?
- Chemical-free product extraction. . . as part of a feedback loop within an integrated microbial system for waste treatment?

Biochar was a recurrent source of debate, in these discussions and throughout the Network’s life. Many funding agencies, including BBSRC, do not regard biochar as biotechnology per se. As one participant noted, “. . .the argument is whether using a biological/organic material as a [biochar] feedstock makes it a biotechnological process. Logically it doesn’t, or this would be equivalent to arguing that cannibalism is a branch of anthropology”. On the other hand, around 21 abstracts or 6% of those submitted to the EBNet ECR conference were related to biochar, compared to less than 2% on the equally topical area of artificial intelligence (AI). EBNet’s Working Group on Biochars for Pollution Prevention also held a joint workshop with the Biomass Biorefinery Network [117] exploring how thermal, thermochemical, and biological conversion technologies may be integrated to improve environmental and economic outcomes of waste and biomass valorisation processes. Other technologies considered included bioleaching of a valuable metal from power station bottom ash, which illustrates the difficulty of adequately capturing the environmental dimension: this is resource recovery aided by microbial systems, but is it necessarily environmental protection? The waste is still likely to contain many environmentally problematic components that make safe disposal no less challenging—but profits from the recovered material could help to offset the costs of further treatment.

Venn diagrams were found to be a useful tool in the discussions, as they could be quickly sketched while removing the need to struggle with precise terminology. Some examples are given in Figure 6. Figure 6a illustrates one view of the relation between Environmental Biotechnology and other environmental engineering and technology disciplines: a perspective similar to that which sees it as evolving from civil or public-health engineering. Figure 6b is a snapshot from continuing debates on the role of synthetic biology in Environmental Biotechnology, in the context of EBNet responses to national consultations on Engineering Biology and of concerns over unjustified exclusion or encroachment [107,108]. Figure 6c arose during discussions on the status of particular products or processes, and the recurring issue of whether Environmental Biotechnology solely or mainly involves pollution prevention and remediation, or also comprises for example the production of energy/materials, even if there is no direct clean-up. Figure 6d shows Environmental Biotechnology not as an object, but a locus between related technology areas. The range of technologies here can be increased to include others such as medical and pharmaceutical biotechnology: but Environmental Biotechnology lies at the heart of this diagram, reflecting its central role in ensuring circularity and sustainability in resource and energy use for the wider emerging bioeconomy.

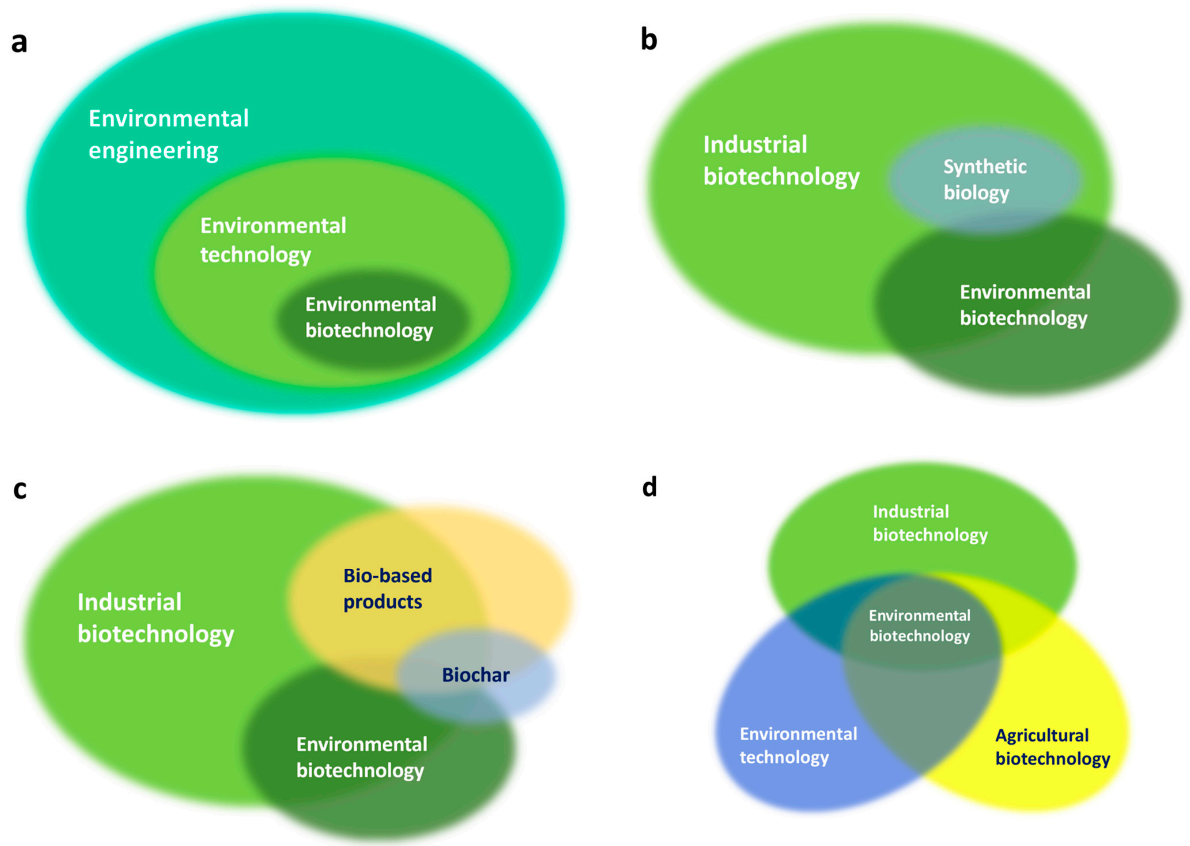

Figure 6. Examples of Venn diagrams from internal EBNet discussions of definitions and remit: (**a**) nested circles interpretation with Environmental Biotechnology as a subdiscipline of environmental technology and within environmental engineering; (**b**,**c**) overlapping circles interpretation, where elements have some overlap, but no element fits fully into another one due to genuinely unique features not present in other elements; (**d**) Environmental Biotechnology understood as the intersection of several technology disciplines.

The EBNet management team debated the value of having a definition or suite of definitions, taking account of the above points. Effective action to influence policy making or funding priorities relies on being able to formulate and communicate a clear common position. It was also suggested that the absence of an overarching definition may support a tendency for people to identify as specialists in, for example, wastewater or soil bioremediation, rather than as Environmental Biotechnologists. This, in turn, may limit cross-fertilisation of ideas and hinder the rapid exploitation of new discoveries and the transfer of new approaches to sister technologies. A further powerful argument was that definitions oblige us to consider what we are doing, and why. A strong case was made for the need to remind practitioners of an overall goal, and thus reduce the time wasted on processes which meet the general definition of biotechnology but do not make sense in terms of contributing to environmental protection and overall sustainability. Examples are numerous, but include research on advanced treatments to enhance biogas production from anaerobic digestion of wastewater biosolids, for cases in which fundamental biological principles mean that the energy input to such advanced treatments will vastly exceed any potential increase in output. Adoption of an overall definition could also help in shifting the historic focus on bolt-on or end-of-pipe solutions, and encourage the use of whole-systems thinking and life-cycle sustainability approaches from the earliest stages of technology development [118].

Based on the Network's experience and the outcomes of the work described, the mini-workshop participants put forward a tentative and preliminary working definition:

> **Working definition of Environmental Biotechnology.** *"Environmental biotechnology can be defined as the use of biologically-mediated systems for the purpose of environmental protection and bioremediation. It includes resource recovery and bioenergy production where these are an integral part of such systems, e.g., to improve their sustainability; and the development of key ancillary technologies to enable these activities: but its primary goal is pollution prevention and remediation."*

Perhaps most importantly, however, it was concluded that, to be of use, such definitions will need to have porous boundaries and be flexible in application. The Venn diagrams shown in Figure 6 were thus deliberately constructed with fuzzy borders and some transparency in the objects, as a means to illustrate this. The ability to select different categories and sub-divisions, and demonstrate relationships by nesting and overlapping, also provides flexibility and promotes interaction and inclusion. Rapid developments in fundamental science and our growing understanding of its complex interactions with technology mean that any definitions must be able to evolve to meet new requirements: thereby also reflecting the evolutionary and adaptive abilities of the biological systems that are so fundamental to this important field.

5. Conclusions

No single widely accepted definition of Environmental Biotechnology was found in the course of the current work, and the literature survey and other activities suggest there is a range of valid understandings for this term, which continue to evolve. Most of these have several common elements, but some of the more outlying examples may cause mutual surprise and perplexity. Some recurrent points of difference, both explicit and implicit, were also identified. These included, in particular, differing positions on (i) whether Environmental Biotechnology concerns microbial systems and products only, or all biologically mediated processes; and (ii) whether it must contain at least some element of environmental protection or remediation, raising the question if processes that focus primarily on resource recovery and valorisation with no direct clean-up or restoration are also core parts of the field. Some of the definitions and descriptions found appeared to be adapted to specific purposes, or to reflect a particular context or community, with a risk of some fragmentation. In many cases, it may be possible to 'nest' these more specific concepts within wider definitions, where a broader and more inclusive description is sought. This approach could also be useful in identifying common elements, e.g., when aspects of a topic extend beyond the boundaries of Environmental [Bio]technology (e.g., as with biochar) or overlap with other fields and disciplines (e.g., bioproducts with Industrial Biotechnology). Venn diagrams can be as useful as verbal definitions in exploring and clarifying our understanding in such cases.

Having a definition or definitions of Environmental Biotechnology is likely to have both advantages and disadvantages, but it will almost certainly be impossible to find one that meets all requirements and pleases everyone. Based on the observations made in this work, however, it is considered that a more formal definition would be of use, for several reasons. It is difficult to advocate for something that lacks a clear definition and a shared consensus on its meaning, or to promote or design policy and other interventions intended to support. A definition is potentially a valuable tool to raise the profile of the area and help counter the lack of understanding and the perceived deficit of glamour which may hinder recruitment, and even funding, both for research and for infrastructure investments. It is clear that neither funders nor the public always understand what the field involves and why it is important and exciting, and here the lack of a shared definition risks manifesting expectations that the subject should mainly perform in a specialists' arena. A definition also provides a sense of identity beyond traditional professional or disciplinary divisions. In the case of Environmental Biotechnology, this broader vision can promote opportunities for cross-fertilisation between different areas of the field, and thus help to accelerate technology translation from fundamental science to large-scale implementation.

It was also noted that any definitions will need to be flexible and inclusive rather than limiting, to allow them to respond and adapt to Environmental Biotechnology's position as a rapidly developing field with a critical central role in the transition to a more sustainable economy. In order to support policy development and implementation, there is a need for definitions and descriptions that are reasonably precise and detailed, like that proposed above—and are thus, perhaps inevitably, slightly pedestrian. In addition, there is a clear need for more inspirational statements, such as those gathered from EBNet's ECRs or found in the literature survey and associated activities. These have a vital role in engaging and enthusing the public and non-specialists, and in helping to convey to them the value, joy and excitement of working in this fascinating and crucially important area.

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Abbreviations

The following abbreviations are used in this manuscript:

AI	Artificial intelligence
BBSRC	Biotechnology and Biological Sciences Research Council
EBIC	Environmental Biotechnology Innovation Centre
EBNet	Environmental Biotechnology Network
ECR	Early Career Researcher
EPSRC	Engineering and Physical Sciences
GBP	Great British Pound
GM	Genetic modification
NIBBSs	Networks in Industrial Biotechnology and Bioenergy
PoC	Proof-of-Concept
UK	United Kingdom
WoS	Web of Science

Appendix A

Figure A1 provides an overview of terms mentioned by members of the Environmental Biotechnology Network to describe their interests. The terms were collected when the individuals joined the network (more than 1300 members). This was done during the standard web-based registration routine; the registrant was asked to express his or her interests by formulating several keywords (free text field). In the word cloud, terms that have been expressed more frequently have a larger font size. The 200 most frequently mentioned terms are shown.

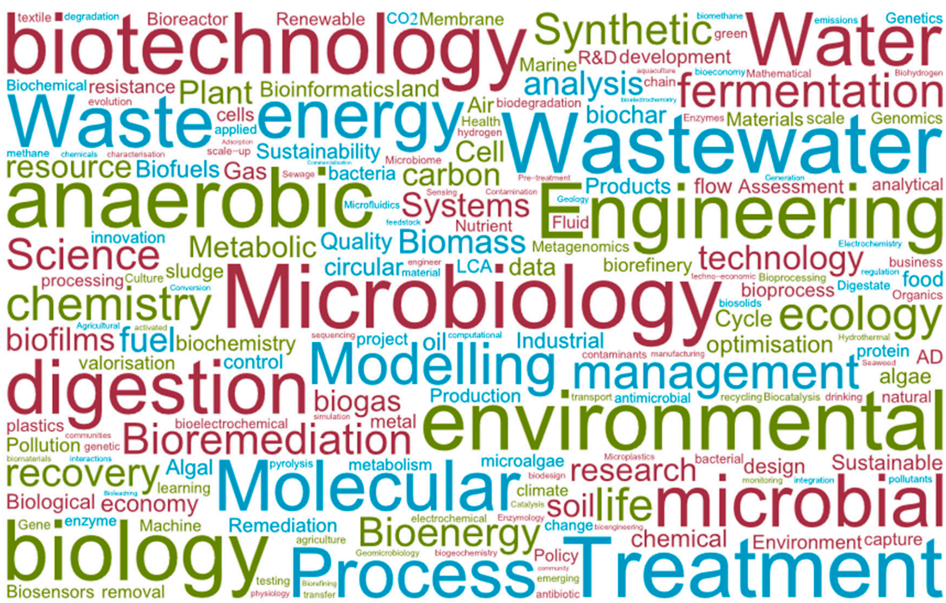

Figure A1. Word cloud produced based on self-declared interests of EBNet members.

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