

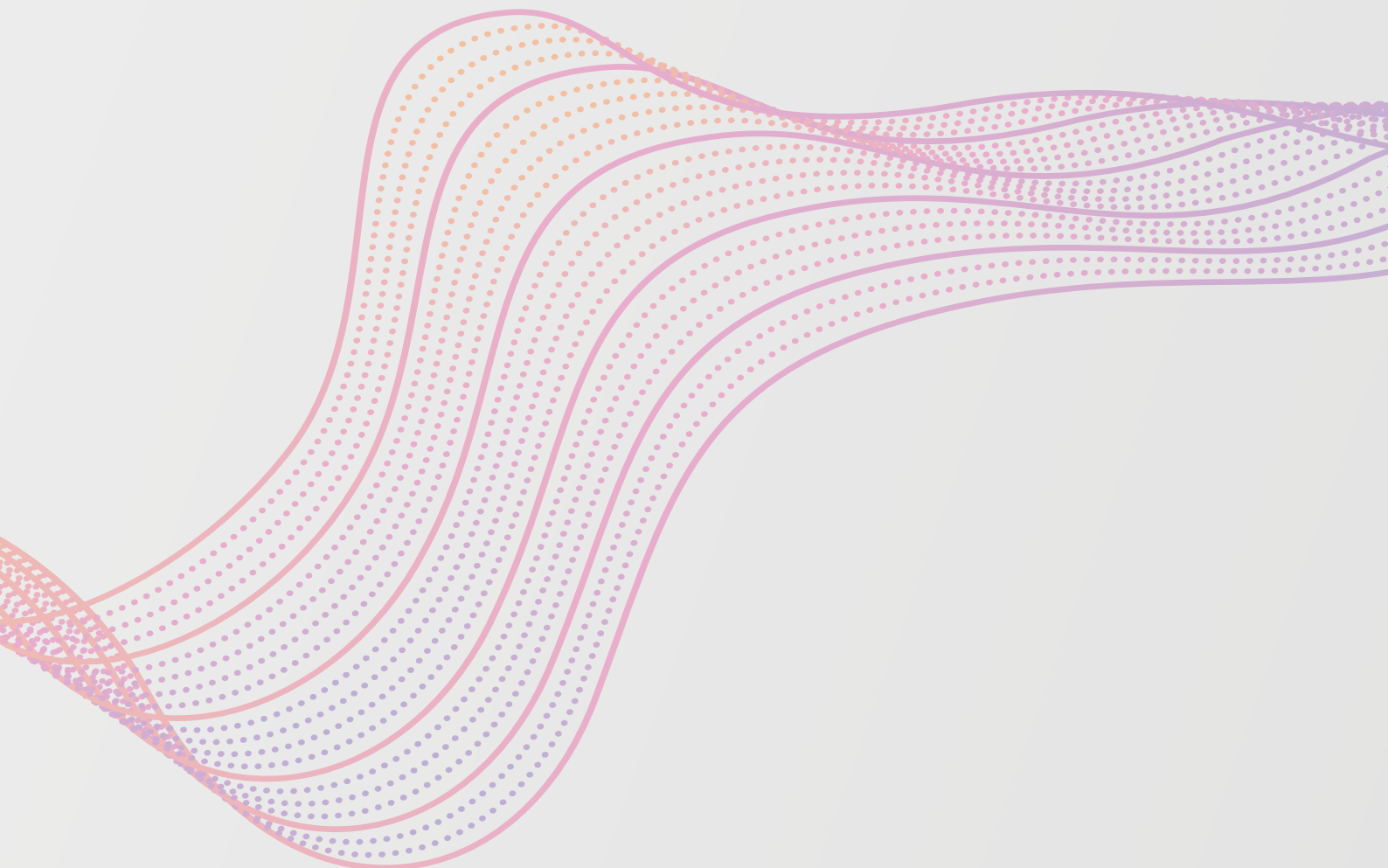


National Biofilms
Innovation Centre

Biofilm Engineering

WORKSHOP REPORT

APRIL 2019 - EDINBURGH UK



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Executive Summary

This workshop was aimed at exploring unmet industrial needs and resulting research questions in the field of Biofilm Engineering.

NBIC partner organisations shared their unmet needs and the 90 attendees (21 companies represented) worked in syndicates to discuss the key challenges and ways to overcome them.

Three main needs emerged:

- i. The need to engineer biofilms for benefit in a human or an animal;
- ii. Creation of a bespoke biofilm community for a defined process outcome or benefit and;
- iii. Improved approaches for investigating, enhancing monitoring or studying biofilms in the engineering setting.

Challenges to overcome in order to address these needs include:

- Developing improved model systems including 'good', 'bad', in-situ, in-vivo, in-silico (both large and small scale).
- The development and standardisation of experimental and monitoring methods including real-time, high-throughput, large scale and multi-variable.
- Improved methods for manipulation of an existing biofilm are critical to achieve relevant end products or results.

Next Steps

1. There is a clear need to bring together more focussed industry/academic groups around the specific industry/sector related problems and needs in Biofilm Engineering which were articulated in the group outputs e.g. on-site systems for recycling of water in a domestic environment. NBIC should coordinate this along with other interested groups (e.g. IBIOIC, WRC, NIBBS and KTN).
2. NBIC should consider and direct how to better influence more structured funding in this area and consider targeting a project call towards Biofilm Engineering.
3. The key themes identified should be built into the NBIC strategy relating to Biofilm Engineering.
4. NBIC support is needed in specific lobbying/outreach in areas such as identifying and releasing funding for fundamental research, creating an appropriate regulatory framework and greater public awareness of opportunities.

Background: National Biofilms Innovation Centre (NBIC)

AN INNOVATION KNOWLEDGE CENTRE (IKC)

NBIC was formed in December 2017 as an Innovation Knowledge Centre (IKC) funded by BBSRC, Innovate UK and the Hartree Centre.

NBIC's mission is to harness the UK's industrial and academic strength in biofilms.

NBIC aims to be the recognised UK hub for accessing biofilm expertise, capability, science and innovation capacity. We exist to catalyse the growth in the UK's scientific, technological and industrial expertise in biofilms with the goal of delivering:

- World class science and scientists
- Breakthrough innovations
- Economic and societal value

We are working to create a network and community of researchers and industrial/commercial partners across the UK and internationally to progress all these elements.

This workshop and our previous workshop on Biofilm Detection (NBIC Workshop Report October 2018) are one key dimension in achieving these goals and are intended to create a forum whereby academic experts and industrial practitioners can meet to explore solving unmet needs.

Biofilms in context

Microbial biofilms and communities collectively represent the largest biomass and activity centre on the planet playing a major role in the biology of the environment (both natural and engineered) and in maintaining public health. Therefore, the understanding of biofilms is key to discovering, controlling and directing the behaviour of microbial communities for sustainable environmental, engineering, public health and medical applications.

Biofilms are central to some of the most urgent global challenges and exert considerable economic impact across industry sectors. Biofilm management is essential to deliver clean and globally sustainable drinking water and food safety and security.

Contamination, fouling, and energy losses by biofilms impact on the £70 billion (UK) food industry, the US \$2.8 trillion consumer products sector, and US \$117 billion global coatings industry. They are also a leading cause of antimicrobial resistance (AMR). As well as these challenges, it also clear that harnessing biofilms for economic and societal benefit also offers significant potential (NBIC Market Report 2017¹).

In trying to both tackle and utilise biofilms the industrial and research community (led by BBSRC/Innovate UK) have defined 4 key interventional strategies:

Prevention: To limit or prevent the early stage microbial adhesion and colonisation events at surfaces. This could employ the use of advanced techniques to create the knowledge-based design of next-generation surfaces.

Detection: To deliver a step change in the ability to detect biofilms directly, in-situ and at the point-of-use in field-based contexts and close-to-patient care through accurate and quantitative biofilm detection and metrology across multiple scales.

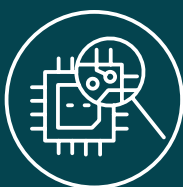
Manage: To destroy, remove or control established biofilms by understanding and exploiting their life cycle dynamics and development across a range of environments and levels of complexity. To accelerate the development of successful treatments, which target the biofilm life cycle-dynamics and intricate structure, through the creation and use of biofilm models resembling real environments.

Engineer: To harness the benefits of complex microbial consortia from knowledge of their composition, function, ecology and evolution. This exploits understanding at the interface with engineering and process applications. It includes improving engineered platforms and solutions e.g. wastewater, biotechnology, resource recovery from wastewater, microbial fuel cells, aerobic and anaerobic biorefinery. The scope for this theme also includes precision tools for microbial community engineering using synthetic biology.



PREVENT

Knowledge-based design of surfaces, interfaces and materials



DETECT

Innovative sensing, tracking and diagnostic technologies



MANAGE

Kill, remove or control established biofilms from exploiting their life cycle dynamics



ENGINEER

Control and direct complex microbial communities in process applications

NBIC's Industrial and Academic Engagement Strategy

A key element of the engagement strategy of NBIC with its industrial and academic community is the exploration of the current unmet industrial, scientific and societal needs in relation to biofilms. Be this the challenges they create or the opportunities they open up. It is NBIC's intent to explore these needs across each industry sector, context and market in order to define what the current state of scientific and technological knowledge is in relation to addressing them. These needs could be for example as diverse as identifying stable methods of preventing microbial attachment to an artificial joint to hand held systems for detecting biofilms in a high-volume food manufacturing plant. Many of these needs will be shared across sectors and some will be unique.

Developing this understanding is aimed at allowing NBIC to better direct its research and translational strategy, as well as facilitating and sharpening its industrial/academic engagement. It remains NBIC's intention to hold workshops and scientific fora around these 4 themes on a rotating basis to deepen the overall understanding around each theme and influence future scientific and translational activity.

The KTN (Innovate UK) held a workshop in York on 27th February 2018 soon after NBIC was formed entitled: 'Identifying and Prioritising Industrial Challenges and Potential Solutions for the Prevention, Detection, Management and Engineering of Biofilms'. In this

report² it is very clear that participants saw it as vital that NBIC should apply attention to the creation of a balanced view of biofilms, whereby they should be addressing not only **the problems** that biofilms present but the **opportunities** which they offer. Biofilms should be viewed as microbial communities that could be exploited for benefit, be that in waste or water treatment, biotechnology, energy production or the manipulation of the human microbiome for health benefits. Biofilms offer a huge transformative economic and societal potential and the literature is crowded with examples of such applications (Edel et al 2019⁴) of "productive biofilms". These range from emerging approaches such as 3D printing of biofilms (O'Neal 2019⁵) which enable the design of bespoke properties all the way to mature industries. One well established example in industry is that of microbial enhanced oil recovery to increase the recovery of oil from oil reservoirs. Conventional primary extraction recovers 5-15% of the total reservoir, secondary methods increase this to 20-60% but microbial enhanced oil recovery takes this further to 35-75%. Use of the method is growing rapidly with annual growth rates forecasts of up to 20% with the market being >US \$1 billion by 2025⁵.

The purpose of the workshop was to bring together a group of interested practitioners from industry and academia to consider the challenges and opportunities for Biofilm Engineering.

Biofilm Engineering Workshop

1.1 SETTING AND AIMS

The workshop was held in Edinburgh on 30th April 2019, starting at 10:00 and finishing at 16:00.

The stated goals of the workshop were:

- To understand the unmet needs and opportunities for Biofilm Engineering
- To create new contacts and relationships
- To identify possible projects and collaborations
- To guide NBIC in the direction of its research and translational activity

The intended outputs of the day were:

- New connections and new collaboration opportunities
- Additions to the evolving NBIC map of scientific/needs landscape
- Agreed priorities and opportunities for translational projects and research investment to influence funders and drive NBIC activities

The meeting was open to all NBIC industry partners and research institutions, with 96 attendees in total comprising 23 from industry representing 21 companies, and 73 attendees from research institutions representing 26 organisations. These numbers had to be limited to fit with the room capacity.

To provide inputs to the meeting, NBIC industrial partners attending were approached to share their needs (Appendix 1). These were collated and sent to all attendees; the intent was to ensure all arrived with an understanding of the range of unmet needs in the engineering of biofilms and had given these some thought prior to the session.

Participants were further asked to consider these needs and to then prioritise their own interest in 4 syndicate session topics which would be running during the meeting:

1. Engineering biofilms for benefit in a human or an animal e.g. health, sustainability;
2. Creating a bespoke biofilm community for a defined process outcome or benefit e.g. energy production, waste water management, recycling;
3. Approaches for investigation, monitoring or studying biofilms in an engineering setting with a broad application e.g. sensing, imaging;
4. Approaches to optimise, enhance biofilms for engineering purposes with broad application, e.g. surface design, stimulation, reactor design.

Attendees were asked to consider the following factors when prioritising their own interest:

- An area of direct interest to me for which I have an industrial/academic need or for which I have a solution/approach or knowledge that can address it;
- An area of indirect interest and my knowledge is applicable from another field;
- A really interesting area and I could learn by participating in the discussion.

There was an initial plenary session led by NBIC (by Co-Director Professor Cait MacPhee, Edinburgh University) summarising and discussing an outline scope of the needs, problems and opportunities in Biofilm Engineering.

There was then a presentation of a Case Study by Professor Ian Head (Newcastle University) on a novel Bioelectrochemical system (BES) to measure organic load in wastewater which received initial support from BBSRC in its very first Biofilms call in 2014 (Appendix 2). This illustrated the huge potential offered by exploiting biofilms as sensors and also the challenges that exist in progressing innovations up the Technology Readiness Level (TRL) chain, a problem which NBIC is aiming to ease for companies.

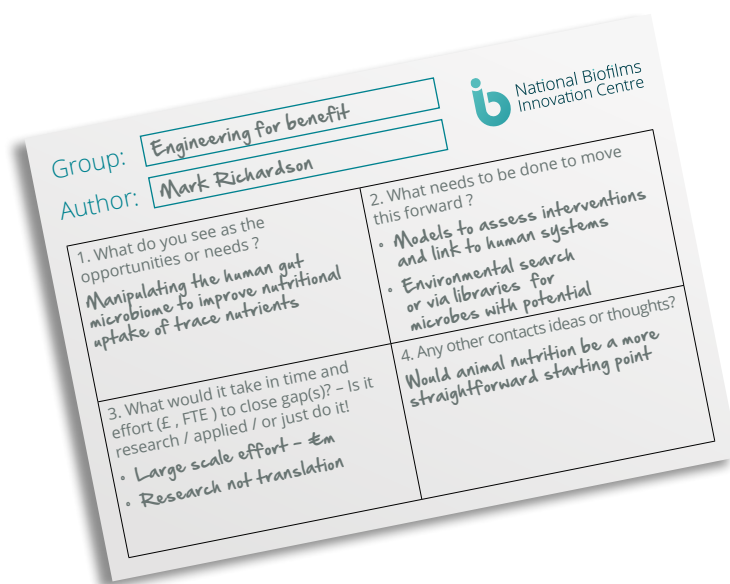
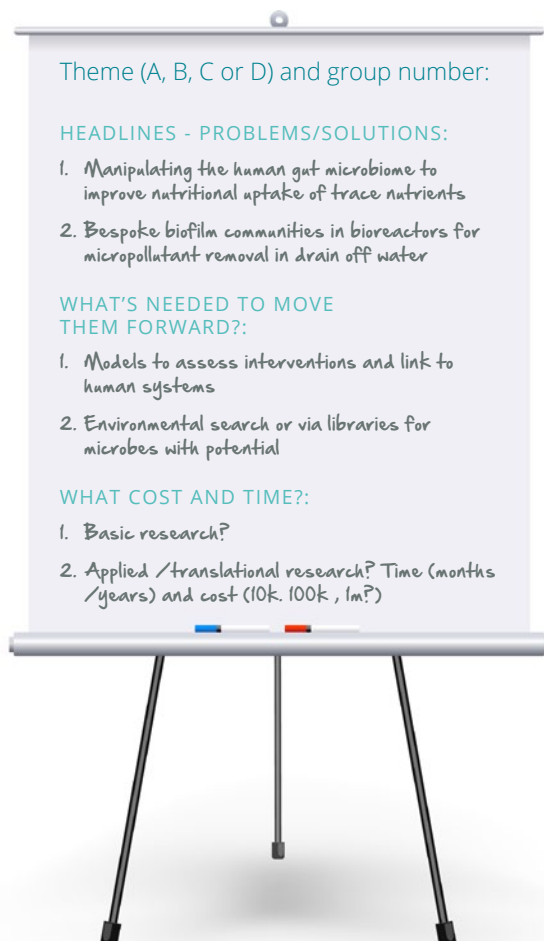
1.2 SYNDICATE OUTPUTS

For the rest of the day there then followed cross industry/academia syndicate sessions on topics 1-4 (above). The syndicates were asked to consider what the key opportunities were in each topic area. These could be described as an unmet need or a problem (i.e. an opportunity exists to solve it). Alternatively, there could be a piece of knowledge, science or technology that already exists (i.e. an opportunity exists to exploit it).

Groups then considered what needs to be done to move each of these opportunities forward:

- Key activities: what are the tasks to be done?
- What type of task is it? e.g. basic research, applied research, knowledge/technology transfer etc.
- What are the estimated costs and timelines?
- What would the priorities be for the group in this area? (This was executed by using voting dots/stickers, 5 per attendee (20 minutes))

This output was captured on a flipchart (collated in Appendix 3.2) and each member also had the chance to create individual feedback on the sheet shown below (collated in Appendix 3.1).



The groups were then rotated to a new area based on their preferences and interests.

Finally, all the output was posted on the walls and all delegates had a chance to post input to problems they had not yet had the chance to review.

The NBIC team collected and organised all the outputs and reviewed and ordered the rankings/votes from the syndicates (Appendix 3.3).

DISCUSSION

In the groups there was much discussion around the challenges facing this field across our different industry sectors. Individual member output is in Appendix 3.1, with group output in Appendix 3.2. The prioritised output from these groups based on the ranking is captured in Appendix 3.3, from which there were six highly rated themes of need and opportunity:

THEME 1

The development and standardisation of experimental and monitoring methods for biofilm engineered systems including real-time, high-throughput, large scale and multi-variable. In agreement with the NBIC workshop on Biofilm Detection there is a strongly articulated need to better monitor and detect biofilms. In this case to allow better process control of a biofilm engineered system.

THEME 2

Improved model systems. This includes those of 'good' helpful biofilms and 'bad' or problem (dysbiotic) biofilms which may need engineering to a healthy state (e.g. in the gut or oral microbiome). "A petri-dish in a lab is very different to large bio-refinery plant" said one attendee. Models need to be robust and cheap and validated on a large scale. They could be in-situ, ex-vivo, in-vivo and mathematical on both large and small scale. These could include human models and models of natural systems. In NBIC's discussion with industry partners across all sectors of biofilm research and translation, we have seen an ongoing call for better model systems in order to allow laboratory findings, innovative interventions or changes to all be tested at an intermediate but relevant scale prior to scale up. The ultimate goal is for changes in the full system to more predictive such that development times can be shortened. Ideally there would be harmonisation across models used by different investigators for the same system and where appropriate, for these to be accepted/adopted by regulatory agencies.

THEME 3

The need for better networking and knowledge exchange. A multidisciplinary collaborative approach is required in setting objectives, defining research and targeting funding including online resource/analysis of previous research. The community needs to be better networked and connected to increase the pace of knowledge sharing and partnership building. This could be achieved by developing small complimentary networks within NBIC. Funding and resources could be pooled to create cross-disciplinary groups/networks to tackle a particular problem/theme.

This could allow the integration of the work of a large research industry community with a specific issue.

THEME 4

Increased understanding of the biofilm in engineered environments. The formation, community composition and inter-species interactions all need basic studies. Current engineered biofilm environments need to be better understood and insights gained and shared for wider application. This need to understand even well deployed systems has always been widely accepted in the field. Henze et al. (2008) for example, commenting on the history of sewage and water treatment, stated: "...new developments are often found by accident and how they work follows afterwards." We need to develop this basic understanding of biofilm communities and their function in a range of different engineered environments. This would include the measurement of microbial metabolites and biofilm markers on different scales (see models, Theme 2), on different surfaces, and in conditions of real-world variability (temporal/spatial).

THEME 5

Exploring methods to manipulate biofilms for beneficial outcomes. This includes the use of surfaces, phage, antimicrobials, creating self-limiting systems, co-cultures with algae/fungus and genetic manipulation. For example, changing the environment or surface conditions to prompt a specific microbiome. These bespoke biofilms with designed or altered properties are required in order to achieve a desired outcome particularly in satisfaction of Theme 6 (below).

THEME 6

Recycling of waste and creation of value-added products including energy. This was a strong theme and is unsurprising as uppermost in the international and scientific agenda is the need for sustainability and the circular economy. It is clear from the breadth of businesses at the meeting and ideas generated that this is an area of huge economic potential. Key targets need to be identified based on the opportunities for achieving maximum impact in line with the state of the current scientific knowledge.

CONCLUSIONS AND NEXT STEPS

Other key points that came out of the syndicates that relate across all these areas were:

- **International outreach:** NBIC should build on its relationship with international centres and other IKCs to ensure the reach of the community is wide and well leveraged.
- **Funding calls:** NBIC Proof of Concept (POC) funding is an important start of the process of translation and engagement. This does however also need to lead onto more/structured funding. NBIC should lead and coordinate this effort. Funds from research councils are needed for multidisciplinary teams with different expertise to make real progress in some of these areas (e.g. analytical chemistry, omics, bioinformatics, engineering, microbiology, bioreactor engineer, hydrodynamics, electrochemistry, electrical engineering). These are significant programmes.
- **NBIC events:** Additional sessions should be held on specific problems. These should be industry directed fundamental questions always seeking a clear commercial end point. They need to be focused with a multidisciplinary team involving different functions (microbiologists, engineers, chemists, etc). Having even more industry partners present would allow the community to understand the needs/business drivers in a safe space.
- **Lobbying:** NBIC can lobby on themes that are aligned to government industry strategy and represent the community in areas as diverse as releasing funding for fundamental research (e.g. microbiome/biofilm research in the dairy and food industry or energy sectors) and articulating the potential of biofilms for plastic degradation.

- There is a clear need to bring together more focused industry/academic groups around specific industry/sector related problems and needs in Biofilm Engineering articulated in the group outputs (note also Theme 3) e.g. on-site systems for recycling of water in a domestic environment. NBIC to review and coordinate this with KTN and other interested groups (e.g. IBIOIC, WRC, NIBBS).
- NBIC should consider and direct how to better influence more structured funding in this area and target a call itself towards Biofilm Engineering.
- The six key themes identified should be built into the NBIC strategy relating to Biofilm Engineering.

REFERENCES

1. Market Need for Biofilm Control Technologies – Report Prepared by PHS Consulting for University of Edinburgh, May 2017
2. Identifying and Prioritising Industrial Challenges and Potential Solutions for the Prevention, Detection, Management and Engineering of Biofilms, May 2018: <https://admin.ktn-uk.co.uk/app/uploads/2018/05/Biofilm-Workshop-Report-May2018.pdf>
3. NBIC Report on Biofilm Detection, October 2018: <https://biofilms.ac.uk/detection-of-biofilms-report/>
4. Edel, M., Horn, H. & Gescher, J. Appl Microbiol Biotechnol (2019) 103: 5095. <https://doi.org/10.1007/s00253-019-09869-x>
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6. O'Neal, B. (2019) 3D Printing Bacteria Biofilms for the Construction of Living Materials, 3D Print.com <https://3dprint.com/250570/3d-printing-bacteria-biofilms-construction-living-materials/> Accessed 06/08/09
7. Henze, Mogens, et al., eds. (2018) Biological Wastewater Treatment. IWA publishing.

Appendix 1: Pre-reading

BACKGROUND

NBIC works across 4 strategic themes - the Prevention, Detection, Management and Engineering of Biofilms. This workshop is targeted to the Engineering of Biofilms where we will focus on the use of biofilms for advantage.

Engineering of Biofilms is concerned with harnessing the benefits of complex microbial consortia from knowledge of their composition, function, ecology and evolution.

Biofilm engineers aim to exploit biofilm understanding at the interface with engineering and process applications. This includes improving engineered platforms and solutions e.g. wastewater, biotechnology, resource recovery from wastewater, microbial fuel cells, aerobic and anaerobic biorefinery.

The scope for this theme also includes approaches for engineering microbial communities using synthetic biology or microbiome manipulation e.g. in the gut, skin.

EXAMPLE OPPORTUNITIES AND NEEDS

Those being addressed by NBIC partner companies are given below some in combination with NBIC Research Partners as funded POC projects. Many others do exist, and will emerge in discussion.

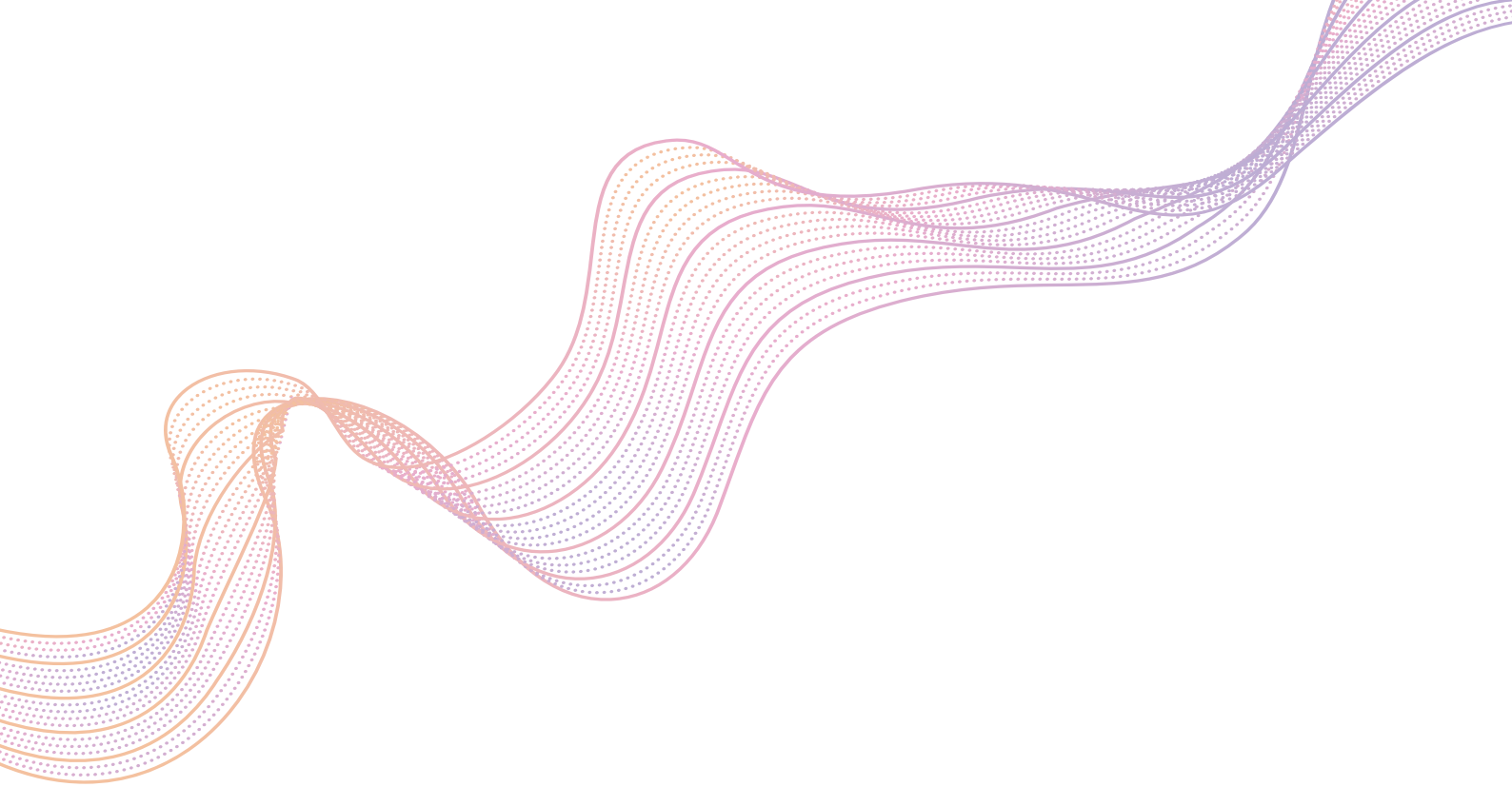
A number of organisations are involved with exploring new opportunities for water treatment technologies. For example, **Veolia** have pioneered **the Moving Bed BioFilm Reactor (MBBR)** technology through its division AnoxKaldnes with a bespoke biofilm community grown on plastic carriers (offering an increased and protected surface area, therefore providing a more compact and robust process) that can be used to treat wastewater in municipal and industrial settings. There is increasing pressure e.g. from the Environment Agency to reduce concentrations of micropollutants, the organic or mineral substances whose toxic, persistent and bio accumulative properties may have a negative effect on the environment and/or organisms. They are present in many products that we consume daily (drugs, cosmetics, insecticides, etc.), at the home or in industry and contemporary analytical techniques are increasingly allowing us to detect these in trace quantities in waste and water. This opens up a **need for** novel approaches to limiting these micropollutants using biofilms.

Varicon Aqua are a producer of Algae Bioreactors and these are used to culture algae for a variety of uses including as foodstuffs and feedstock for animals. Step changes in efficiency and ease of manufacture could be made if these could be grown on surfaces as biofilms rather than in suspension as planktonic cultures and this requires **the need** for a multidisciplinary approach and **better understanding of how to optimise**

surfaces for better engineering of attachment and growth. Translation of learning from other sectors could be key here. Varicon have been awarded an NBIC POC project fund for collaborative work with Plymouth Marine Laboratories on the development of a Moving Membrane Bioreactor (MMBR) for the automated cultivation and harvest of algae grown as a biofilm.

Carbogenics are an example of a company working to engineer biofilms for anaerobic digestion of farm and food waste and sewage sludge using a specialist biochar (pyrolysed biomass) called **CreChar**. This is derived from organic wastes such as paper and cardboard waste and can engineer enhanced methane production from the digester biofilm community due to its surface properties. This shows the need for methods for engineering more efficient and productive biofilms in industrial settings and the opportunities for novel surfaces and designs in achieving this outcome.

Recircle has a patented biotechnology that uses a proprietary bacterial isolate that selectively removes sulphur from thiophenic compounds from fuel oils. It is using such bacteria to treat waste rubber and affect desulphurisation of rubber to enable reuse of the sulphur cross-linked polymer. This process allows recycling of waste rubber from discarded automotive tyres. It allows higher incorporation rates into new high value rubber products than recycled rubber from via other current approaches. The team are also looking at ways to exploit other biotechnological properties of bacteria in their collection. This demonstrates what a rich resource the natural environment can be, and the **need for identifying organisms for engineering biofilms for benefit.**



Moy Park are concerned with poultry health and production and are interested in maximising the benefits of the microbiome in the animal gut and engineering it to benefit poultry health, welfare, sustainability, minimise environmental impact and limit feed use. They are also working alongside producers and many organisations towards the One Health Agenda which requires considering multiple stakeholders in the food chain. **Needs include the improvement of upstream food safety by reducing the downstream occurrence of endemic human pathogens**, such as campylobacter in poultry. Microbiome control is an opportunity.

AB Agri are an example of a food company who operate across the whole food chain and are interested in the need for alternatives to antibiotics as influencers of the microbiome and for growth promotion and prophylaxis. Innovations in this sector include the addition of bacteriophage and antimicrobial peptides as feed additives (in the US). One “vision” is to be able to understand rapidly in-situ the composition of the microbiome of the animal. This, via contemporary techniques, might allow us to understand what is the “healthy” and “unhealthy” microbiome and then be able to engineer it for health via dietary intervention.

Tata Steel and Newcastle University have won funds to explore the treatment of zinc-contaminated slurry in steel production by a Bioelectrochemical system (BES). Basic Oxygen Steelmaking (BOS) generates significant amount of dust with high Fe contents. The presence of zinc limits Fe recovery as it would cause operational issues, leading to large amounts of dust being stockpiled. The team propose a novel

and sustainable BES (integrated systems combining wastewater treatment with energy generation and resource recovery) to tackle this challenge.

Yoghurt production generates wastewater that requires considerable energy to clean. **Bioloop** and UWE have won funds to look at cleaning dairy waste using bacteria that release electricity as a by-product. They will examine which groups of bacteria (biofilms) are best at producing power and where to find them in Yeo Valley’s wastewater treatment plant.

Finally, Sheffield University and **Welsh Water** have an NBIC funded POC project to explore the routine addition of phosphate to drinking water to minimise lead dissolution from household pipes. This can as a side product favour microbial biofilm formation in drinking water systems. To optimise the way this chemical is used by water utilities the team aim to understand its impact on biofilm formation and on water quality and safety.

Appendix 2: Case Study

BIOELECTROCHEMICAL SYSTEMS (BES)

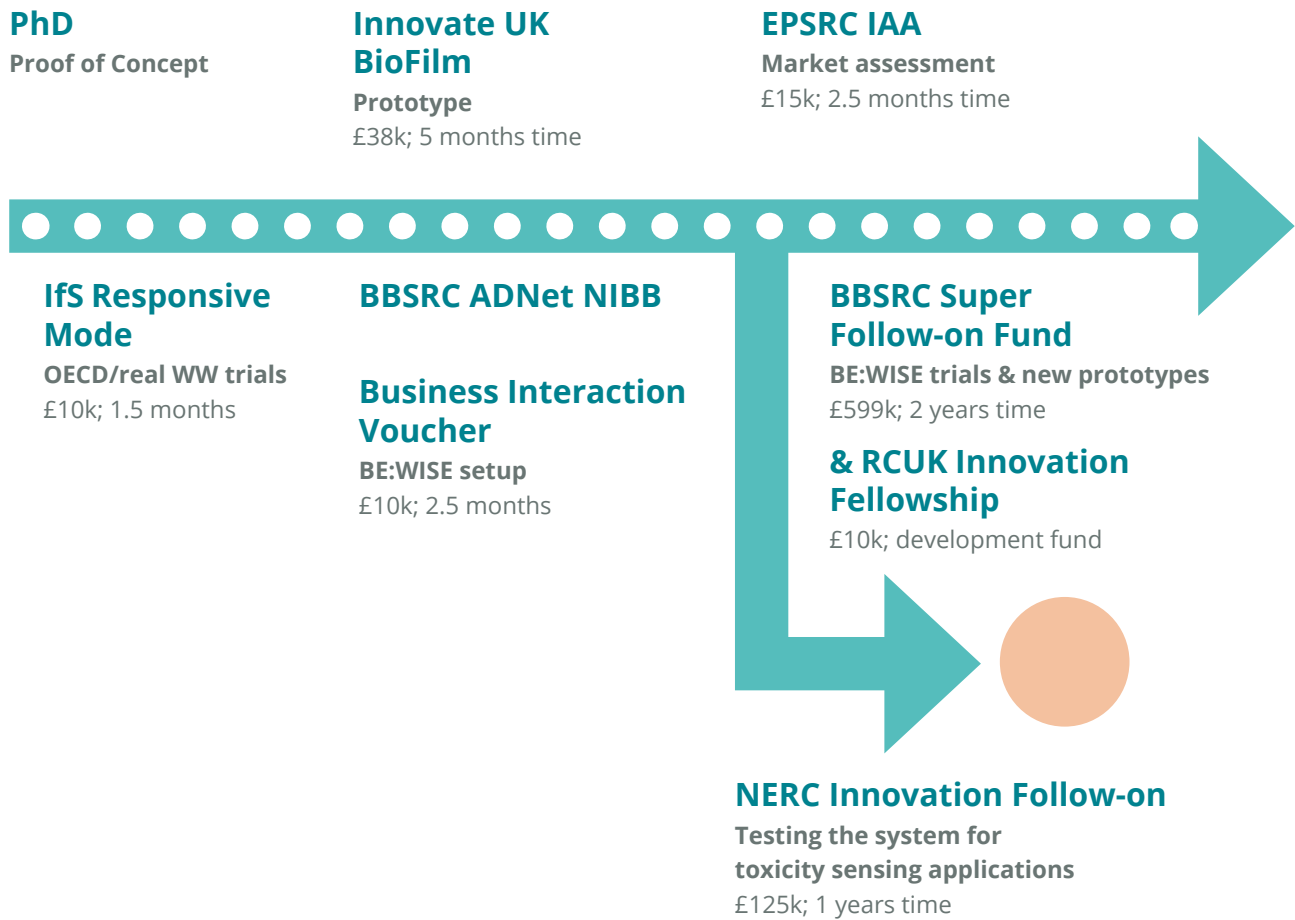
Ian M. Head (Professor of Environmental Microbiology and Dean of Research & Innovation Newcastle University) gave a presentation entitled: **Bioelectrochemical systems for sensing applications; half a league, half a league, half a league onward**. Collaborators: Martin Spurr, Alexiane Godain, Eileen Yu, Keith Scott, Tom Curtis Hitesh Boghani, Rodrigo Fernandez Feito Drigo, Amandeep Kaur, Richard Dinsdale, Alan Guwy, Chris Jones, Rob Johnson, Ronald Daalmans and Iano Premier.

Bioelectrochemical systems (BES) harness the power of microbial catalysts in electrochemical systems and rely on natural processes involved in organic carbon turnover in anoxic environments, rather than using chemicals as oxidants or energy sources as in normal metabolism organisms in BES use electrodes as a sink or source of electrons They can also use materials in a range of waste streams as fuel or ultimate electron sinks. Ian described the innovation journey for the Newcastle team in conjunction with a range of partners to develop a biosensor based on BES with initial funding which came from first round of BBSRC biofilms programme in 2014.

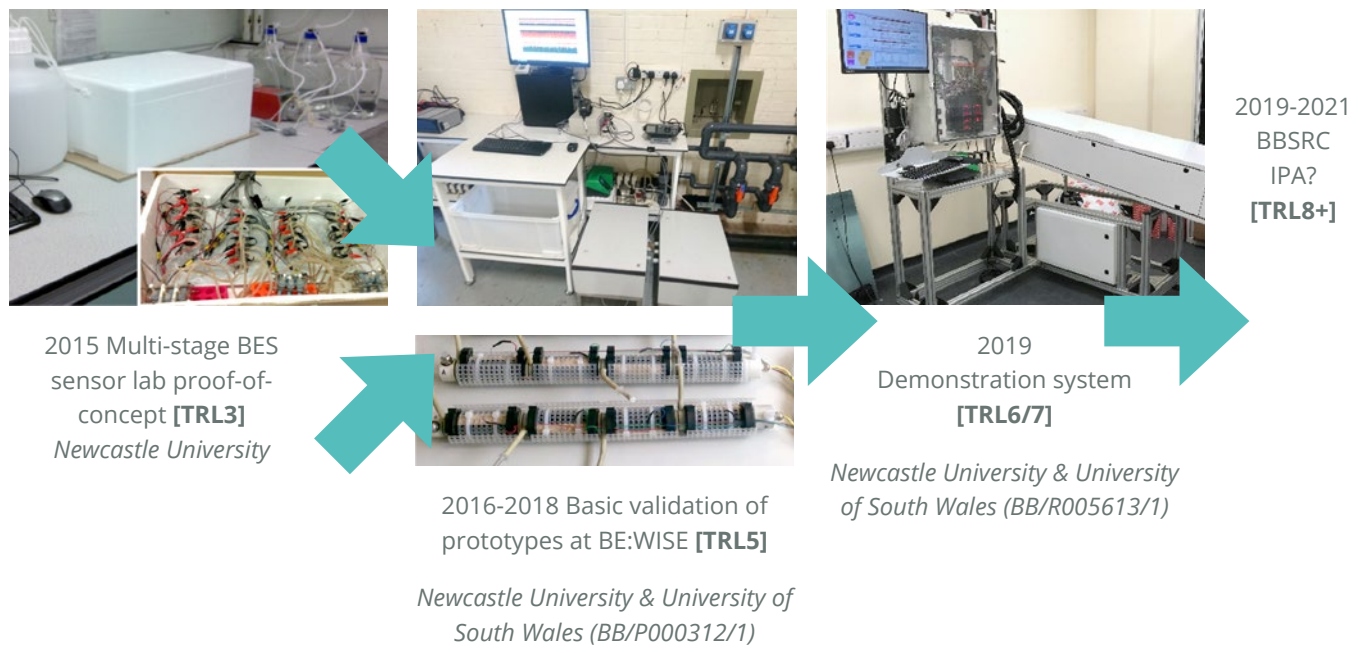
BES can be used to measure organic load (BOD/COD) in wastewater (1) Electrical output is proportional to organic load. Issues of scale up are much less than for large scale energy generation; (2) The market for organic load monitoring in wastewater is potentially large. Wastewater treatment plants which treat greater than 2000 p.e. (population equivalents) are required to report compliance data with organic load in effluent. 21% of the 9,000 waste water treatment plants in the UK are large enough to report compliance data and there are 71,000 treatment plants in the EU. They established a Proof of Principle in the laboratory and developed the system for field deployment and initiated collaboration with colleagues at the University of South Wales, Northumbrian Water, the AD Network, BEWise, WHP and Chivas Brothers. They have had a number of ups and downs on their innovation journey (Fig. 1) and Ian reported they now have BBSRC Super Follow-on Fund from Dec 2017 – Dec 2019 and a full field trial with early prototype BES sensors complete (Fig. 2).

1. Di Lorenzo, M, Curtis, T.P, Head, I.M. & Scott, K. (2009) A single-chamber microbial fuel cell as a biosensor for wastewaters. *Water Research* 43: 3145-3154
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BIOELECTROCHEMICAL SYSTEMS FOR SENSING APPLICATIONS – FIG 1



BIOELECTROCHEMICAL SYSTEMS FOR SENSING APPLICATIONS – FIG 2



Appendix 3: Syndicate Outputs

APPENDIX 3.1: INDIVIDUAL FEEDBACK FROM BREAKOUT GROUPS

Group Title

- A. Engineering biofilms for benefit in a human or an animal e.g. health, sustainability.
- B. Creating a bespoke biofilm community for a defined process outcome or benefit e.g. energy production, waste water management, recycling.
- C. Approaches for investigation, monitoring or studying biofilms in the engineering setting e.g. sensing, imaging.
- D. Approaches to optimise or enhance biofilms for engineering purposes e.g. surface design, stimulation, reactor design.

Group	What do you see as the opportunities or needs?	What needs to be done to move this forward?	What would it take in time and effort to close gap(s)?	Any other contacts, ideas or thoughts?
A1	Greater understanding of the basic biology of biofilms. Low temp plasma. Methods to eradicate biofilm(s). Bioelectrical processes. Waste water (analysis and treatment).	Scaling on core resources e.g. 1. Nanopore - sequencing 2. Bioinformatics 3. Multi-omic platforms (including TraDIS and NMR) 4. Next generation imaging (Microscopy etc.).	Some more targeted conferences/symposia.	Increase relationship with SCELSE (Singapore Centre for Environmental Life Science Engineering). Explore the possibility of engineering and screening for compound/ approaches that support biofilms. Surface- Planktonic model microbiome? 3D printer: Bulk pathogens. Design structure and function.
A1	Probiotics. Explore beneficial networks of micro-organisms in real systems. Metabolomics and proteomics.	Integrated "omics". Modelling and patterns.	Applied research / real world applications.	
A1	Metabolomics study to identify new metabolites in actinobacteria biofilms.	Tool up metabolic technologies.	Pilot study £20-50k.	Need pharma partner.
A1	Need to understand the basics of microbiomes and the interactions between different organisms - exploit these interactions to exclude organisms of concern.	Basic research into understanding these interactions.	£50k is very small to make a real impact but an important start of the process.	

Group	What do you see as the opportunities or needs?	What needs to be done to move this forward?	What would it take in time and effort to close gap(s)?	Any other contacts, ideas or thoughts?
A1	Probiotics for hygiene. More omics to the individual targets - applied areas. Epigenetics of biofilms for positive material outcomes.	Communities of practice - multidiscipline workshop. Projects have to contain all disciplines.	Student/ PostDoc funding in capability groups. Leverage community. £50k.	Communication - specific PhD studentships - all form teams.
A1	NBIC lead on growing capacity in interdisciplinary skills: training week-bioinformatics, large data sets. Multi omics on biomed samples (need trained people/staff and analyses=; > £50K)	Skilled staff (see box on left). Multiple groups. Similar analyses/approaches to be able to share and use each other's data.	>£50k. People/Staff and analyses.	
A3	Surface manipulation to encourage the right kind of bacteria: Rough surfaces, hydrophobic surfaces. Precision engineering - target a particular community.	Collaboration between micro and materials science. Inconsistencies between experimental methods. Require standardised model systems.	Change/manipulate environment to prompt a certain kind of microbiome. Ref. to altering skin care/body products.	Need to successfully culture/ identify a lot more bacteria. Haven't really demonstrated what a 'healthy' microbiome looks like. Try and link human genome to human microbiota. More studies required.
A3	Need for understanding health • Multiple health states. • Changes over life course. Need to accept that biofilms will be precision engineering of microbiome. Environmental factors (e.g. water treatment) what impact does this have on the microbiome?	Identify key features of probiotic or beneficial organism - need combination of lots of studies with microbiome analysis. Must include mechanistic studies. More correlations between human genome and microbiome.	Combination of lab research and applied studies. This is a large area, so difficult to specify a product.	
A4	Bioremediation - experiments and increased throughput. In-situ measurements - what do you measure? - medical device. Physics/maths models for colony - simple but representative and predictive. Standardization and correlations? Anti-biotics - manipulation in/out? - Phages Variability?... Failure analysis/prevention.	Methods for manipulating and selecting? - Skew ecology. Measurement development. Enterobiotix, but some others? Gut health?? Define: What is a biofilm ART human/animal analyst. Applied research - basic research. Poor level 1 research.	Narrow focus - multi-disciplinary community - build? £50K, Industry. Very early stage! Basic research? Aiming for application too early. In-vitro model. High throughput platform development. Simulation models.	Enterobiotix IBioIC?

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A4	In-situ analysis of biofilms/microbiome. Antibiotics/manipulating biofilms. Modelling biofilm formation and dynamics in response to stress e.g. physical stress.	Develop small complimentary networks within NBIC. With common interests. Maybe pool funding and resources. New collaborations. Multidisciplinary work. Develop basic understanding of biofilm communities e.g. on skin.	Basic research - more needed. Biofilms in different environments poorly understood. Some early applied research could be carried out. e.g. looking at how changes to biofilm community affects skin.	Maybe try to develop small intra-networks within NBIC. Cross disciplinary groups to tackle a particular problem/theme. Maybe with POC with more funding than 50K between groups.
A4	Better representation of extra polymeric substances (EPS). There is a clear need for good models based on first principles.	Invest in good people who can talk to both the language of experiments and unauthenticated models.	Research. 10-12 months of a research associate to pave the way for a bigger application.	Having a framework for cross-disciplinary talks.
A4	(v. complex communities) Other than gut health, other areas are still in early phase e.g. skin health. Also unknown is how the home-biome affects human health and if malnutrition of home biofilms can benefit. Needs clear understanding of important/relevant biofilms and measurements needed to develop models and begin assessing number of variables.	Understand who is playing in this field (with some, but not majority input from gut health sector). Dedicated workshop with clear definition of the problem and 'wants' from industry and academics.	Workshop. Multiple/connected POC projects to leverage max input/recourse capability.	
A4	Ecological changes to the biofilm. Predictive in-vitro model. Multiple variables. Robust models.	Development of in-vitro models with defined characteristics. Control over as many variables as possible.	Significant amount of basic research required to define biofilm formation, composition, stimulants and beyond before involving an industrial partner. 3 years, £1M.	Events should be held on specific problems (e.g. skin biofilm, oral biofilm) with a focused multidisciplinary team involving microbiologists, engineers, chemists etc.
A4	Manipulating biofilm with/without antibiotics. Complex systems many with variables. We need a way of increasing speed and number of experiments.	Antibiotic free manipulation needs industry to lobby government to release lots of money for fundamental research. High throughput experiment - seed funding to test potential new platforms (e.g. acoustic manipulation or microfluids).	Antibiotics - Loads of money over many years but it is important. High throughput - seed funding then big grants for most promising ideas.	
A4	Real-time in-situ measuring and monitoring. Manipulate biofilms without antibiotics (i.e. alternative methods). Understand the biofilm structure and mechanism better.	Develop new alternative methods to engineer and/or destroy biofilms community either on the skin or in the gut for health benefits. To scope the industry needs and challenges and formulate them into research projects.	Fund and time (2-3 years). Both research and applied but move towards applied context related research.	Applying phage and phage proteins/peptides for biofilm destroying or microbiome engineering (skin or gut). Human/animal e.g. health/sustainability.

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A5	Biofilms to modify surface properties - functional materials. Sustainability - waste water treatment using biofilm communities.	Tools to study surface properties.		
A5	Diagnostic tools. Intraspecies biofilms communities in human health. Defining biofilm formation/adhesion properties of the biofilm. - Surfaces - Model Systems. Inhibiting biofilm formation - medical devices. Smart surfaces to prevent biofilm formation. Waste streams in different industries i.e. beverages - How biofilm formed. Waste water treatment - biofilm microbial communities.	Translational studies - In-vitro - In-vivo. Model systems that replicate inside the body.	Research - Just do it. It will take time. Forums to interact with others.	Networking. Funding.
A5	Robust, online measurements for processes involving growth or other aspects of bacterial transformations. Rapid tests, repeatability and safety.	Work with device manufacturers to create reliable methods for measurement that can be operated remotely or with little intervention.	Work on demonstration for a single industry sector. POC - 3 years. £1.3-2.0 million for total project deliverables.	Work with stakeholders like CPI. Bring learning from other sectors: Human health/oral health. Target large/industrial sector applications.
A5	Develop smart surfaces to prevent biofilm formation or promote biofilm formation.	Interdisciplinary collaborations with industrial partnerships.	POC project (6-12 months) - EPSRC grant (3 years).	Multiscale measurement tech.
A5	Opportunities: Microbial consortia needs to be analysed by a group of scientists with different expertise. Needs: A common platform, funding and suitable training.	An all encompassing consortium to be set up to move this forward along with lots of funds. Training of suitable students for working in this consortium.	Time: At least 5 years. Effort: A very combined effort coordinated by NBIC. Funds: From different bodies like BBSRC and EPERC.	
A5	Appear to be a bespoke biofilm need by companies for treatment of specific issues in their waste water e.g. high ammonium content. Alternatives to chemicals/biocides with changing legislation.	Also consideration of the longevity of biofilm - use of phage/other bacterial, fungal and algal predators; use of equivalent of a prebiotic in biofilm design.	Mainly applied - quite focused projects targeted at specific industry sectors e.g. chicken, feather, dairy, waste, animal bedding waste in industrial scan animal/bird production.	

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A5	Multispecies biofilms in health. Translational healthcare.	Model systems - humans and animals. Better understanding of human and animal physiology.		
A5	Waste in industry in general e.g. water, whiskey, pharma. Energy cost reduction. Circular bio economy.	Industrial/academic collaboration. Scale up to industrial/commercial scale.	Academics should wait until trials before looking to scale up and at that stage engaged with design engineering companies to get costs. 7-10 years to scale up.	Early discussions with industry to understand what is in the upstream process. Reduction of energy costs would be the driver in waste/recycling. Collaborate with the IB sector - they are keen to know what is in the waste streams.
A5	Veterinary science - easier routes to market than humans. Regulatory pathways not as complex. Diverse field. Wound healing - to promote healing development.	What are the key problems that need solving e.g. gut health in large animals. Linked to carriers and other diseases like CJD, diabetes, what else?	Need to focus on translational pathway so progression to impact.	
A5	Need to understand the different microbiome communities in the different parts of the body in humans or animals i.e. skin, gut, respiratory etc. Then identify the key weak areas to target. Then engineer a biofilm which could attach, colonise and help sustain health or engineer a biofilm containing key bacteria which produce key anti-microbial molecules to kill a given pathogen of a given disease or produce molecules which are deficient in a given disease.	Understand the tools available. How to improve them.		
B1	Using biofilms for waste water treatment and subsequent/parallel generation of energy and value added products.	Industry partners with need for waste water treatment. Identifying biofilm communities capable of degrading the micropollutants. Proof of Concept.	Applied. POC funding. Masters/PhD student. Scale up from bench to pilot.	

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B1	<p>Continuous vs batch monitoring.</p> <p>Infinite analytes - what are the measures?</p> <p>Env/process eng. for film selection.</p> <p>Products - Energy? Chemical? H2O? Algae? - Renewable product.</p> <p>Plastics recycling.</p> <p>Bio-remediation.</p>	<p>Materials Chemistry.</p> <p>Focus big to small OR small to big.</p> <p>Anaerobe/non efficiency vs energy savings/generation.</p> <p>Communication of needs and opportunities in 2 way communication between academic and industry. Regulation.</p>	<p>Regulatory environments.</p> <p>TEA.</p> <p>AD Capacity.</p>	<p>Isle, Oxentia.</p> <p>Alex Conradie.</p> <p>TEA/markets.</p>
B1	<p>Does chlorination of tap water influence the human microbiome. A systems study.</p> <p>Engineering and human microbiome and chlorine fluorides suppression.</p>	<p>NBIC funds large project. Collaboration with Water Industry/BBSRC UK.</p>	<p>£2 million or £500,000 project.</p>	
B2	<p>Food industry: New product, new processes, treatment. e.g. chicken farmers - feeding systems contaminated.</p> <p>Sustainable water usage in small 'communities' e.g. hospitals, prisons, hotels. Safely reduce water use - pathogens, limescale etc.</p> <p>Microbial solutions for fat, oil, grease.</p> <p>Can we reverse the microbial process for self healing concrete-bungs in sewers in order to degrade concrete? For enhancers using yeast- Craig (MacDonalds, Seven Trent)</p>	<p>Translation from thought experiments to real world - engagement with industry.</p>	<p>More workshops - understanding needs business drivers in a safe space.</p> <p>Sharing of industry ideas/across industry.</p>	
B2	<p>Monitor communities for development of AMR genes/non-culturable bacteria.</p> <p>Tools to monitor.</p> <p>How to keep biofilms stable.</p> <p>Modelling of bespoke communities.</p>	<p>We need translation - NBIC is helping - something like clinical trials phases but for biofilm in environment.</p>	<p>Translation - more workshops with industry and academia.</p> <p>More joint projects - PhDs (NBIC POC are great).</p>	
B2	<p>Transferring knowledge from biofilm research in different areas e.g. ideas tested in environmental settings taking forward in medical areas (i.e. microbial migration routes in a formed biofilm).</p>	<p>More cross-disciplinary contracts, talks, projects.</p>		

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B2	More exchange academia - industry. Creating toolboxes for detecting/ managing/engineering biofilms.	More workshops specific co-funded calls.		
B2	Transition from academia to industry: <ul style="list-style-type: none"> Needs to be quicker. Opportunities need to be created. 	Co-funding/collaboration of academics and relevant industries. More industries need to attend this type of workshop. Specific workshops can be created.	Just do it. Actions need to be taken to increase networking between industries and academics. Better communications between industries and academics.	
B2	Bioaugmentation of beneficial strains would help the process but more studies needed to evaluate the augmentation effect on process in terms of efficiency/ stability of community/process.	Run experiment to augment the special species in the lab in reactor. Monitor the reactors community/efficiency. To evaluate the stability of the augmentation.	It would require time and money. It is research and application in the field on large/pilot scale can be tested.	
B2	For consortia: <ul style="list-style-type: none"> Library of organisms with known functionality and predicted interactions. Population control mechanisms against contamination. 	Access to industry setting for testing academic ideas: <ul style="list-style-type: none"> Without committing to commercialisation. Like 'clinical trials'. Petri dish in lab very different to large biorefinery plant. Monitoring technologies to respond changes in consortium performance/contributions.	Dedicated test facilities - very costly? <ul style="list-style-type: none"> Who would fund every day testing? 	
B4	Creating biofilm help with sustainability. Need to understand microbial/metabolites under different conditions - scale, surface, variability - temporal spatial. Key is function. Modelling is important/information from above to feed into this. Getting more out of waste e.g. recycling, reusing. Upstream chemical understanding of waste ("homebuyer's report for waste").			

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B4	How to manipulate biofilm community to achieve a specific purpose, not just from engineering aspects in a black box but also from microbial perspective such as bioaugmentation.	Integrate microbial manipulation with engineering tests (reactor, operational conditions).	3-5 years. Applied.	
B5	Waste treatment. Alternative treatment for infections.			
B5	Local bespoke clean-up (e.g. on farm, on site). Plastic recycling, plastic disposal, marine microplastics. Waste - product processing. How do we do coral regeneration/support? Soil optimisation.	Phage - regulatory barriers e.g. phage to model bespoke communities. More data (again).	e.g. soil requires fundamental research (££). Waste disposal POC fairly straightforward (water at least!)	Q: Does this require 'biofilm' vs 'microbes'? NB. There are soil improvement products extant.
B5	Waste by-products: <ul style="list-style-type: none"> • Poultry better degradation, better than spreading on land. • Feathers - breakdown into more useful compounds. Surface application: <ul style="list-style-type: none"> • Reducing availability of available sanitisers. • Utilise biofilms in drains in high risk. • Phages. 	On farm waste handling - difficulty with biosecurity? Current legislation (phages) needs to change.		
B5	Phage opportunities? PR; Lytic phage. Biofilm/bio population for plastics recycling. AS for different unit operators. Algal biofilms? Bioreactors? Biofilm for surfaces - genus's bio?	Clarity on benefit/business case. <ul style="list-style-type: none"> • Size of challenge/business case - waste water and pre-biotics What is the right biofilm/microbial population for algal bio evaluations.	POC: Waste to products. Understand the ideal scenario/status that makes a good soil - microbiome.	Pre-biotic to enhance the desired microbiome. <ul style="list-style-type: none"> • Multiple industry. • Connect with agricultural industry that would be more responsive to this. Bring in fermentation companies. Industry directed fundamental revelational questions!

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B6	Developing a standard formation of measuring methods. Research the attachment process so we can enhance it or decrease it depending on the specific goals.	To develop robust and cheap technology that allows measurement of desired conditions in real-time. Do research in a standardized way prior to testing new conditions.	Applied research, at least 3 years to test the technology of then scale it up. Optimisation of systems.	Consider biofilms of other organisms like microalgae.
B6	Biochar for WWTP. Recycling: Magnetic biochar can be separated from liquid/ aqua conditions. Regarding on energy production, it is needed to provide addition habitat for microbes growth. Biorefinery.	Monitoring the process. Analysing. Collaboration.		
C1	A key challenge is having appropriate methods to characterise the transient composition of biofilms in different environments e.g. industry, health, food.	Use advanced genomics to validate and create a 'finger-printing' technology for rapid characterisation (e.g. using biomarkers). This is in line with similar techniques in medical sector.	3 year project (Proof of Concept) 4-5 FTEs Industrial stakeholders £0.9 - 1.5 million	Target sectors like 'dairy' and foods with important film formation problems. Biodegradable plastics: align to industry strategy. How to use films for biodegradation of plastics.
C1	Standardisation methods for cultivation/ destruction/measurements - robust and cheap to allow a large scale approach. Scale up.	To develop appropriate technology specific for each sector i.e. fingerprinting techniques to measure specific compounds that allows monitoring the biofilm.	Applied research with industrial collaboration. It is dependent upon the sector i.e. the bioplastic degradation with the objective of integrating the output with microbial composition, the Proof of Concept would take 3 years, 20 FTEs and £10 million.	
C1	1. Standardisation of methods for studying biofilms. 2. Standardisation of methods for studying the transient nature of biofilms. 3. Monitoring individual heterogeneity (persisters) within biofilms.	POC call - 3 years Interdisciplinary cooperation between groups, industry and stakeholders. - Microbial communities - Chemistry - Engineering.	5-7 years Research (multiple PhDs) Stakeholder input and funding	
C1	Translation from bench scale to industrial level. • Refining lab procedures to make them reliable and cost effective.	Identify a sector which has a deficit in the detection of biofilm at large scale - propose an approach to help with the desired outcome i.e. disruption of biofilm.	If the idea is focus in the detection of fingerprint that will allow to evaluated the stability of biofilm it should be at least 3 years for POC and a multidisciplinary team of at least 10 people.	Focus on one sector at a time would help to focus in a time-reliable method that might be worth to explore across different ones once it has been validated at large scale.

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C1	Detection of potentially harmful biofilms within water systems.	Development of a cheap, rapid and thorough system. 2/3 would be okay. Integration and development of current technologies.	Research/ applied/scale up. 3 years, 3 FTE Bio conductance, inline bioreactor, RAMAN microscopy Total cost: £1million	May be applicable to PALL and Vedia.
C1	Standardisation of evaluating biofilms. Creation of standard biofilms i.e. polymicrobial community. e.g. evaluating efficacy of antimicrobials (screening).	Development of standardised methods that can be adopted by every lab. A global acceptance of adopted technology.	It will consist of all the elements stated above: 5 year time frame. £5 million. Group of 20 FTEs	Universal acceptance that antimicrobial screening should be undertaken on biofilms as opposed to planktonic bacteria.
C2	Generating stable microbial communities which can give you a desired output. Scale up issues from the lab to the industrial environment obtaining the same output. Opportunities are around using omics, analytical chemistry technologies e.g. Raman, 3D-OrbiSIMS, DepSeq etc which needs to be integrated with the handling of big data.	Generate stable communities which give you a desired output and as a start point look at a way to measure this by looking at biomarkers of stability. Finding strategies to avoid the collapse of the community.	For a Proof of Concept i.e. generate a stable scalable approach you would need around 20 FTE with different expertise: analytical chemistry, omics, bioinformatics, engineering, microbiology with a budget of at least £10M/3 years.	If we really want to address this issue we need the integration of the work of a large research/industry community starting with an specific issue. We did discuss conversion of bio plastics into energy.
C2	Do we fully understand the 'problems' we are trying to find solutions for?	Tech transfer - the 'so what' - how to make impact? Start with the end in mind and the ways in which funders, industry and investors will be supportive.	Maybe a slightly different way for us all to think?	
C2	Develop novel optical biofilm analytical methods using emerging technologies much as hyperspectral imaging.	Collaboration between biofilm scientists, optical scientists and instrument manufacturers.	There is some R&D involved but many applications in industry.	
C3	Needs: Which monitoring methods are currently available? Which sensing and imaging? <ul style="list-style-type: none"> Detection challenges. Disinfection (effective). Scaling up is often a problem and distribution (supply chain). 	We need to determine available technology e.g. phage technology. Molecular approaches (bioinformatics processing is not user friendly). Simple tests (in-situ).	Research	

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C3	<p>Need to acknowledge that bacteria/biofilms are present and interact with engineering/engineered systems.</p> <p>Opportunity: Hear from industry on opportunities for process enhancement - product quality and opportunities for new microbial processes.</p> <p>Interdisciplinary working - wealth of chem.</p> <p>Characterisation techniques exist and can be harnessed.</p>	<p>More opportunities for academic - industry interaction.</p> <p>More academic interdisciplinary forums to identify and cross-apply characterisation techniques.</p>		
C3	<p>Methods to analyse biofilm production.</p> <p>Identify mechanisms in a variety of organisms and compare them.</p> <p>How to prevent biofilm production.</p>			
C3	<p>Field based, rapid sequencing.</p> <p>Understanding of microbiome and biofilm function.</p> <p>Omic's</p>	<p>User friendly platforms/interfaces/software that can be interpreted by companies, field researchers and engineers.</p>	<p>RCUK</p> <p>BBSRC/ MRC/ EPSRC</p> <p>PostDoc 1-2 years, £200k</p>	
C5	<p>Developing existing technologies to environmental biofilms.</p> <p>Can you target organisms that start biofilm (attachment; first organisms in biofilm succession) so you know when begin and take action.</p> <p>Or use quorum sensing chemicals in some way - using lab techniques and taking to field. Are technologies cheap, quick and sensitive for the field?</p> <p>Contamination can be a problem.</p>	<p>Funding.</p> <p>Taking lab techniques to the field.</p>	<p>Research.</p>	
C5	<p>Biomarkers that are robust and ideally generic.</p>	<p>Basic research.</p>	<p>Significant research.</p>	
C5	<p>Non-invasive in-situ analytical techniques for rapid identification/analysis of biofilm genotype/phenotype/behaviour.</p>	<p>Ability to develop technology at the interface:</p> <p>Biology - Physical - Data - Control - Science - Analysis.</p> <p>To develop a device to measure something about biofilms.</p>	<p>Potentially collaboration between disciplines and between academia and industry.</p>	

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C5	In-situ imaging of biofilms.		Research, money, time.	
D1	<p>Surface design, mimic the environment.</p> <ul style="list-style-type: none"> • i.e. intestinal tract/ epithelial layer/ dental plaques. • functionally similar (mucus secretion). • poly community - identify these microbes. Poly microbial communications. • modulating function from food stuffs or health benefits, during disease. 	<p>Reflective models - collaborations - multidisciplinary - engineering, medicine, chemists, microbiology, bacteriologist, virologist etc.</p> <p>Core fundamental research - further the knowledge.</p> <p>Industrial engagement.</p>	<p>Directed (by industry) research.</p> <p>Trial and error with modelling systems.</p>	<p>Strain bank (?).</p> <p>Marine sector: Accept fowling. Probiotic approach. One that signals.</p> <p>Dentistry: Not removing biofilms. Currently focus on determining healthy - on route to rationally design interventions. Enzymes that degrade the matrix. Identify beneficial characteristics. Saliva coating, any implant/surface design in order to take this into account.</p> <p>Two diametrically opposed biofilms trying to 'control'.</p> <p>No grasp of what this community is. Roughness caused with compliance, knowing what is in them "community indicators".</p> <p>How do you characterise biofilm (physiochemical, bio species)</p> <p>Marine sector, uncertainty (shark?). Data collection/ analysis. Multi-omics. Cost of omics data. Tie to drag consequences 'surrogate marker for drag'.</p> <p>Engineering self-limitation - engineering the community competition. Understanding inter species interactions.</p>
D1	<p>Surface properties to allow and destroy biofilm.</p> <p>Multiple microbial biofilms could also help in making it rigid/easily removable (genetic engineering).</p> <p>Use of microbbles for cleaning.</p>			
D1	Surface engineering - pro attachment for industry processes.	<p>Knowledge transfer/funding.</p> <p>Industry engagement.</p> <p>Need informing on the challenges.</p>	<p>Core research - do i - short to long time scale. ££.</p> <p>Industry engagement - med-long. Cost is time.</p>	Additional workshops - preventative/ attachment to speak.

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D2	<p>Need: identify surrogate markers.</p> <p>Need: methods to engineer biofilms towards maintaining non-harmful.</p> <p>Complex biofilms tend to be robust.</p>	<p>Large-scale omics studies to find correlations (what is good vs bad biofilm?).</p> <p>Screening to find methods (chemical or physical) to modulate biofilms.</p> <p>Rapid bioassays.</p> <p>Computational models to predict complexity.</p>	<p>Extensive omics research (e.g. in marine sector) will require significant funding.</p>	
D2	<p>Engineering communities for a beneficial outcome e.g. promote competition for control or self-limitation.</p> <p>Manipulating the conditioning layer to select for beneficial species.</p>	<p>Understanding what's in there.</p> <p>Coming up with a parameter that reports on beneficial/ detrimental impact. (Species, macro molecules, metabolites).</p>	<p>Pre-competitive research, large scale effort, omics approaches (research £££).</p> <p>Search for functional indicators (without necessarily understanding a direct link).</p>	<p>We mainly discussed marine/dental systems.</p> <p>Start with fresh water systems instead (but industry pull?).</p> <p>"Accidental community engineering" (example of drinking fountains in Switzerland).</p>
D2	<p>Understanding anti-fouling in ships and marine environments.</p> <p>Huge (>\$1billion per year) financial cost at present.</p>	<p>Data!</p> <p>Understanding of marine biofilm compositions (species, genes, enzymes, products, EPS) over space and time.</p> <p>Understanding of the impact of environment.</p> <p>Understanding interaction with the ship surface.</p>	<p>Lots of money!</p> <p>International problem. Need an international approach?</p> <p>But even incremental improvements can have significant improvements.</p>	
D3	<p>Difficult to go from small scale in bioreactors to large scale.</p> <p>Not all bioreactors work with high levels of water, need to consider low water and marine environments.</p> <p>Issues with standardised models.</p>	<p>Need to do more work on modelling of bacterial communities and outputs that can inform on the development of bioreactors.</p> <p>Can identify commonalities between different models and bacterial communities to help establish the basics to develop new models.</p>	<p>To optimise a microbial fuel cell to work towards the generation of electricity in a small village using waste water from a plant nearby, you would need 5 FTEs from which would include engineers, modellers, surface designers, modellers, microbiologist for 3 years with around £5M not everybody would need to work the 5 years.</p>	<p>MUST use NBIC to address these big issues by identifying researchers which specific expertise which can work for just a few months in a very large project to do specific parts and NBIC could enable identifying the need, the researchers and support to apply for funding e.g. IUK.</p>
D3	<p>Generation of biochemicals.</p> <p>Bioreactors for biofilms, microbial immobilisation.</p> <p>Materials for microbial adhesion.</p> <p>Stability of biofilms as mono cultures or consortia.</p> <p>Maintenance of biofilm in active state.</p> <p>Monitoring of biofilm, porosity of biofilm.</p>	<p>Engineering of reactors, construction of artificial biofilm formation.</p> <p>Testing of functionality of bacteria and longevity.</p>	<p>Much basic R&D needed that would protract project.</p> <p>3-5 years for monoculture biofilms.</p>	

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D3	Waste water treatment in a commercialised saleable method i.e. consumer waste systems for houses with bacteria to clean water.	Cross functional meetings with industry and academia to align scopes to maximise output and time/cost efficiency.	Research Workshop and trials: 6 months, £50k	
D3	Understanding of some general principles that can be translated across different domains. Needs coordinated interdiscipline involving both experimental and theoretical researchers and modellers.	Coordination of a multidisciplinary team that can work in a way only possible through something like a national centre and not industrial. More discipline constructed projects. Materials, statistics, biologists, modelers, engineers, hydraulics/ mechanics, expertise in analytics - chemical, physical, biological.	5-8 years. Probably 3-4 FTE but not all with 100% effort over the full 5-8 years - needs a different model outside the '3 year postdoc focused proposal'.	
D3	Model systems. Low water/saline studies.	Community agreement. New studies and international links. National facility investment in mobile researchers that can move between projects/ institutions.	Just do it! - community meeting to decide on model systems. POC small studies/ larger study for different low water/ saline needs/ opportunities.	
D3	Bioreactor design.	Engineers, scientific experts (15 staff).	10 years. £5.6 million.	
D3	Need in the industry for access to expertise and resources in knowledge in biofilms and how to test. Physical samples. Especially SMEs do not have the knowledge or resource for small/ adhoc tests.	Academic/ industrial collaboration or listing of institute expertise and equipment. Small funding grant for access to equipment. Training in general expertise.	Could be implemented immediately with coordination with partners in the NBIC.	
D3	Optimisation of bioreactors using interdisciplinary expertise.	Large level of expertise from interdisciplinary team (microbiologist, bioreactor engineer, hydrodynamics, electrochemistry, electrical engineering).	6FTE, 10 years, £6M.	
D4	Promoting positive biofilms through surface patterning and chemistry. Scaling route for surface fabrication.	Additional (focussed) discussion/ networking groups. Outputs from this. More industrial interactions. Interdisciplinary interactions.	6 months for ideas then 5 years funding £5M. All 3.	

Group	What do you see as the opportunities or needs?	What needs to be done to move this forward?	What would it take in time and effort to close gap(s)?	Any other contacts, ideas or thoughts?
D4	<p>Cross discipline objectives - networking, brainstorming.</p> <p>Biofilm formation/control.</p> <p>3-D printing structures - functional.</p>	<p>More discussion opportunities.</p> <p>Novel method for selection of species e.g. methanogens.</p>		<p>Commercial funding: engagement with industry.</p> <p>Funding landscape relayed: is there sufficient interest? Output.</p> <p>Format of discussions.</p>
D5	<p>Explore the possibility of engineering and screening for compound/ approaches that support biofilms.</p> <p>Surface- Planktonic model microbiome?</p> <p>3D printer to generate 'surface structures':</p> <p>Design structure and function experiments.</p>	<p>Challenge outputs around biofilm indicators.</p> <p>Microbials for biofilm regeneration.</p>	<p>This is a relatively modest call (in terms of funding) to deliver a very important network.</p>	
D5	<p>Simulations: deduce general principles. Biology and chemistry combined.</p> <p>Explore parameter space.</p> <p>Scale up</p> <p>Generalised principles: 'all'</p> <p>- Agree on a few key</p> <p>Questions. Everyone works towards that and have shared goals. (Do not reinvent the wheels).</p> <p>Maldi-Mass spec: how to see/ get 'in' the biofilm to analyse?</p>	<p>Fund teams. Single cell to large communities.</p> <p>LINK these</p> <p>More skilled workforce.</p> <p>Good collaborations.</p> <p>Context/consistency/models</p> <p>- Role and wise use?</p>	<p>Linking micro to engineering.</p>	<p>Goals: Unify to help field move forward (academics with industry).</p> <p>Everyone contributes (making use of all their skills optimally - this is "bluesky"; idealism).</p> <p>How to avoid 100 studies that can be used by someone else?</p>

Appendix 3: Syndicate Outputs

APPENDIX 3.2: GROUP FEEDBACK FROM BREAKOUT GROUPS

Group Title

- A. Engineering biofilms for benefit in a human or an animal e.g. health, sustainability.
- B. Creating a bespoke biofilm community for a defined process outcome or benefit e.g. energy production, waste water management, recycling.
- C. Approaches for investigation, monitoring or studying biofilms in the engineering setting e.g. sensing, imaging.
- D. Approaches to optimise or enhance biofilms for engineering purposes e.g. surface design, stimulation, reactor design.

* = Votes from Syndicate members

Group	What do you see as the opportunities or needs?	What needs to be done to move this forward?	What would it take in time and effort to close gap(s)?
A1	<ul style="list-style-type: none"> • Probiotics for hygiene. <p>Huge variability. Limited by analytical mechanism - longer read informatics (meta economics). Nanopore.</p> <ul style="list-style-type: none"> • What is good/bad microbiome? <p>What is the community? Better analytical microbiome. Target genomes - What and How? Understanding the community - Interactions in poly species. Target different aspects that influence the biofilm.</p> <ul style="list-style-type: none"> • Move to multi omics*. • Food and factory hygiene - cleaning. • Presentation - Triccosan example; "TraDIS Express" survival and growth; phenotype and genotype. • Human microbiome - gut health, disease, wounds. What biofilms are beneficial? • What does SO-look project get us to in multifactor issues? • Amelenate gene transfer. • Unlocked epigenetics/ xxxx xxxx at the right time. • Bacterial changes at surface. <p>Factors that affect biofilm - Understand your biofilm (universality, bioinformatics, emerging properties). Beyond model - Biofilm you want to understand or evaluate? (applied). Basic model to real model (Stimulate biofilms [what metabolites?], application conditions).</p>	<ul style="list-style-type: none"> • Understand Your Biofilm Workshop*** - biophysical course for labs discipline, x - discipline. - Case studies from these. Cross SCELSE, UK and others. • Community cultureomics** - Proteomic study - insight. • PR Executive to MRC/Wellcome - leverage to something bigger. • Analyse microbiology - biomedical. • PostDoc support - Market research. • Metabolomic studies - 	

Group	What do you see as the opportunities or needs?	What needs to be done to move this forward?	What would it take in time and effort to close gap(s)?
A2	<ul style="list-style-type: none"> • Can an artificial biofilm restore barrier function in the gut (animal and human)?* • Design of 'good' biofilm on medical devices instead of engineering clean novel surfaces to stop biofilms.** • Microbial causes of chronic disease: How do we know what ideal is? • Stopping 'bad' biofilm growth on collagen sausage casing and in waste water.***** OR, can we manufacture 'good' biofilm growth on casing by selecting specific conditions to promote certain growth? • Using cellulose as a scaffold for biofilm in different applications? Also chitin can be used or a combination of cellulose and chitin.** 	<ul style="list-style-type: none"> • Need to increase knowledge of microbial systems in oral and gut. <p>Shouldn't use predetermined 'good' and 'bad' microbiome - is our current understanding flawed or biased? Need new technology to study full microbiome.</p> <ul style="list-style-type: none"> • Hypothesis driven development. • Technology that gives this info in-situ.* Currently use sampling but it's easier to sample from ill people and harder to collect samples from healthy as the procedure can be invasive. • Can we add an artificial barrier to the gut instead of relying on the body synthesizing one? • How do we deal with scale and monitoring i.e. gut very large. • Possibly oceanography technology?* • Temporal and spacial variability. • Standardisation of tests* i.e. in human gut system many different studies through the whole gut. Info not always comparable e.g. breath testing vs faecal testing. Bacteriophage used to maintain biofilm over time. Biofilm doesn't have to rely on genetic mutation but selective growth. 	<p>Large scale project/research for gut in vivo experiments.</p> <p>Shorter term project - sausage casing.</p> <p>Cellulose scaffolding (cellulose on TRL scale already).</p>
A3	<ul style="list-style-type: none"> • Manipulate microbial community so that it maintains health.* <p>Surface manipulation to encourage the right kind of bacteria (rough surfaces, hydrophobic surfaces).*****</p> <p>Precision engineering - target a particular community.</p> <ul style="list-style-type: none"> • Collaboration between micro/ materials science. • Reduce inconsistencies between experimental methods.* • Require standardised model systems.***** • Change/ manipulate environment to promote a kind of microbiome***** (reference to altering skin case/ body products). • Need to successfully culture/ identify a lot more bacteria. • Haven't really demonstrated what a 'healthy' microbiome looks like.** • Try and link the human genome to human microbiome. More study required. • Link between chlorinated disinfectants and gut microbiome. Studies between areas/ countries that are chlorinated/ non-chlorinated. 	<ul style="list-style-type: none"> • Much more fundamental research. • In-vitro models. • PhD / Post Doc. 	

Group	What do you see as the opportunities or needs?	What needs to be done to move this forward?	What would it take in time and effort to close gap(s)?
A4	<p>Problems</p> <ul style="list-style-type: none"> • Real time, in-situ measurement - ecology.* <p>What to measure, how they interplay and what effect they have on biofilm.</p> <ul style="list-style-type: none"> • Mock (of in-vitro) community predictive of in vivo* - Simplified but still predictive. • Antibiotics - How to manipulate biofilms with and without antibiotics. • Standardisation of biofilm/robustness. • Very complex interactive process - how to navigate in a much more intelligent space. <p>Solutions</p> <ul style="list-style-type: none"> • HT e.g. microfluidic approaches to assess as many variables and create models/ algorithms.***** • Manipulate (or potentially skew ecology) selectively e.g. phage.* e.g. skin health, oral health. • Investigate what has been done previously and by whom? How successful (and what has been measured).* • Good biofilm definition. e.g. skin health. 	<ul style="list-style-type: none"> • Physical and chemical. • NBIC dedicated workshop to identify who/ where/ what and help to develop links and POC projects. • Industry/better definition of the problem - workshop and/or working groups. Try to move workshop away from gut health. • Glasgow Uni PhD bridging funds (Bill Sloan). • More complete characterisation of the biofilm e.g. EPS (highly variable) - physical properties and metabolic activity. 	<p>£50k+ £50k+ £50k = £150k project (can be multi-sectional).</p>
A5	<ul style="list-style-type: none"> • Bioindustry waste: Farms, beer, food etc.* <p>How the biofilms form - identify what make them*.</p> <p>Waste water - How to produce energy. Transforming from toxic waste.</p> <p>Isolate new product.</p> <p>How a new product can be produced via biofilms.</p> <ul style="list-style-type: none"> • More academic-industry collaborations. • More cross-disciplinary collaborations to reduce biofilms. • Develop new surfaces to prevent biofilm formation e.g. medical devices. • Waste water treatment. • Robust online measurement for processes: Bacterial growth and transformation. Rapid test, repeatability and safety. Share knowledge and transparency.* • Veterinary sciences (Luxury market for pets): Treatments, nutrition, potential transferable pathogens from animals to humans. • Dental field: Entry to the body and diseases. Diagnosis, treatment, wound healing. • Understand communities: Single/ different strain - Tools for diagnosis. • Exploit biofilms: Drug delivery e.g. vitamins, antibiotics. Use as a genomic tool? • Diagnostic tools to understand interspecies communities. 	<ul style="list-style-type: none"> • Fundamental science has to happen but develop new ways to study biofilms. New and more model systems. Move away from laboratory flask (although needed) to cell cultures, human models and nanomaterials.***** • Spending money in a more targeted manner, more specific towards applications and making sure it is going to bring results/ data/ outcomes.* • Use the different tools and models to bring knowledge together, share knowledge and try and answer key/ big questions - Less money spent in non-useful science.** • How close can we come to these model systems? 	

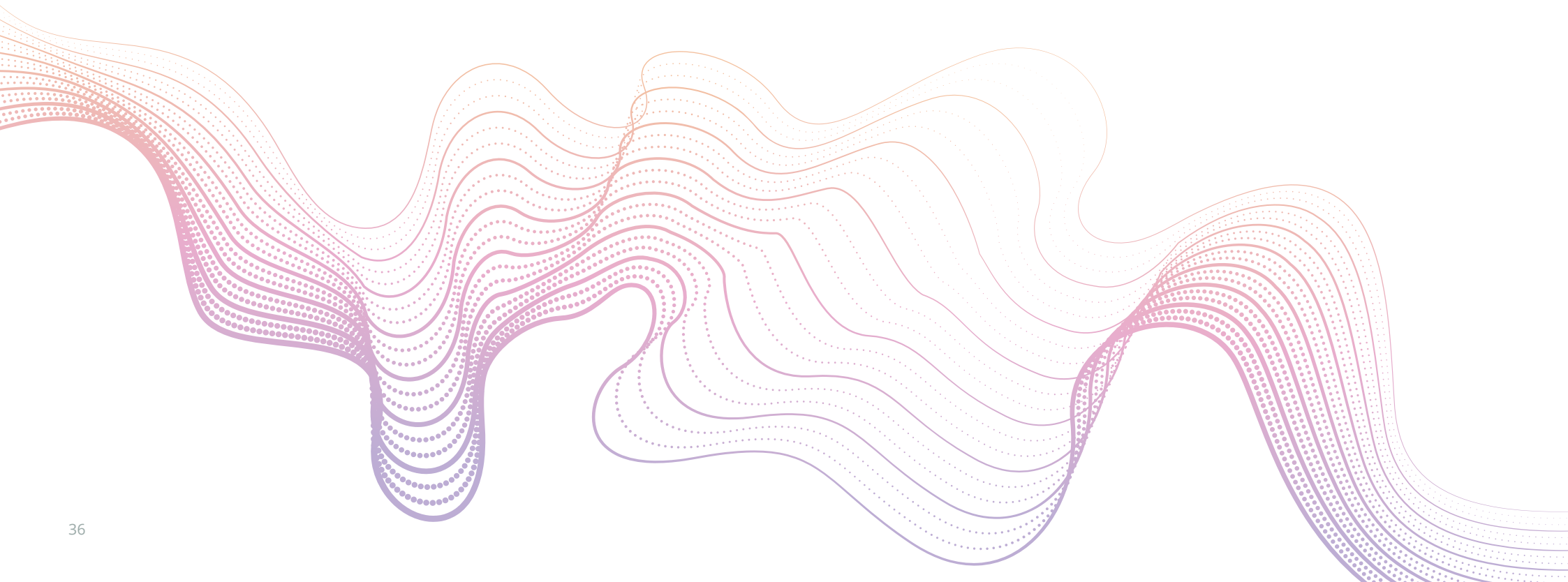
Group	What do you see as the opportunities or needs?	What needs to be done to move this forward?	What would it take in time and effort to close gap(s)?
A6	<ul style="list-style-type: none"> Encapsulating biofilms for internal use in the body.* <p>Production of a metabolite/hormone as a result of some signal e.g. insulin.</p> <p>Responsive, unlike tablets.</p> <p>"Cell factory".</p> <p>Personalisable?</p>	<ul style="list-style-type: none"> A biofilm persister production facility. Slow growth. Easily genetically modified. Easily encapsulated: Capsule impermeable to toxins. Capsule is a source of food - degraded, once degraded human immune cells then kill bugs.* Cells are contained. Reproducibility between humans. Want a biofilm for tolerance. "Klingon" coating that shields/ disguises from the immune system. Model systems: biomeforming, low production of antigens. Break correlation between growth and metabolism. Genetic system for expression e.g. 77 and mutagenesis to prevent division. {microbiology}. Develop ideal permeable encapsulation material {material science}. Cross discipline approach. 	<p>Networking opportunities to foster discussions and collaborations on biofilms.*****</p> <p>How often? And How Many?</p> <p>Narrower/ wider focus.</p> <p>What format? More talks? More open table discussion?</p>
B1	<p>Bespoke Biofilm</p> <ul style="list-style-type: none"> Scale up. Monitor: Continuous. Batch. What to monitor? Tools: Quantity of bacteria in the biofilm. Next generation sequencing. Process: Bioinformatics. Recycling. Product vs function. Oil and nuclear cleaning. Bioremechanisation. Value added products e.g. Waste water (factory - energy generation). <p>"Factory thinking" in waste water and energy generation**</p> <ul style="list-style-type: none"> Enhance current biofilm community: Increase attachment and lower EPS, increase sticky EPS with lower absorption. Phenol waste water. 1/2 energy to treat this. Anaerobes. Increased efficiency. Value added products*****: What are these? Change community to provide and not degrade these. Energy (e.g. methane). Food - protein production. Challenge: Mixed SSP cohort. Regulations. Maintain consistent population. 	<p>Waste water and energy generation</p> <ul style="list-style-type: none"> Understand current mixed biofilm. Optimise SA for growth. More time and money. Clear commercial end point. Material optimisation. Algae? Communication: Academia and industry. Expertise: Quantifying biofilm communities, engineering, waste water, market sector experts (commercial). <p>How to recover phenolics in a more economic way</p> <ul style="list-style-type: none"> Contacts: Textiles conferences, investors, commercial team. Experts: Microscopy (ESEM). Textile partners for trials and samples. Other markets: Value chain development. Biofilm community: Engineer. Many small communities. % phenolic degraders? Function. 	<p>How to recover phenolics in a more economic way</p> <ul style="list-style-type: none"> POC: £50K, 1 year. PhD: £100K, 3 years. Pre-commercial: £750K. Small scale trials. Commercialisation: £3-5M.*

Group	What do you see as the opportunities or needs?	What needs to be done to move this forward?	What would it take in time and effort to close gap(s)?
B2	<ul style="list-style-type: none"> • Environmental opportunities: Waste water - Clean and reuse. Sustainability. Yeast system: Fat-bergs, concrete-bergs. • Translations: Growing biofilms - lab - applications? Natural communities - unknown/competition - bespoke pairwise consortium.* • Monitoring: Academic approaches too slow for industry? Accuracy vs speed. • Preventing invasion/ contamination: Learn from oral biofilms? Don't want to breed resistance! Pre-sterilise prior to seeding? • GM issue: CRISPR. Academic tools. How 'closed' is application - water vs energy. 	<ul style="list-style-type: none"> • Quick access to industrial setting: To check academic ideas - Petri dish vs biorefiners. ***** Not a committed commercialisation. Clinical trials equivalent. • Easier access to industry partnered funding. • Monitoring of consortium over time: AND ability to respond. Biosensors (strains, genetic reporters) embedded within consortium. 	
B3	<ul style="list-style-type: none"> • Prevention of biofilm formation e.g. hospitals, biofouling.* • Systems for on site recycling of water e.g. domestics.***** • Control of biofilm communities. • On site detection systems to find distribution.* • Simulation/use of models to describe microbial biofilms* - Level of understanding required for models?? • Genetic approach to engineer biofilms.**** 		

Group	What do you see as the opportunities or needs?	What needs to be done to move this forward?	What would it take in time and effort to close gap(s)?
B4	<ul style="list-style-type: none"> Reliable monitoring - develop models of data.***** Academic - industrial collaboration events. Scalability. Functionality of bioreactor parameters - How to revive functions. Sustainability. <ul style="list-style-type: none"> Chemistry of upstream waste water. Sustainability. 	Funding issues.	Timeline: 7-10 years.
B5	<ul style="list-style-type: none"> Prebiotics to enhance desired microbes. Agri-tech industry. Waste treatment e.g. water, litter, feathers, by-products.*** Surface applications for competitive inhibition/exclusion of harmful bugs.* Algal/ fungal/bacterial symbiotic mixed kingdom of biofilms.* 		
B6	<p>Problems:</p> <ul style="list-style-type: none"> Decarbonisation, CO2 to produce chemicals. Electrochemical control of reaction. CO2 fermentation/ N2 production. Chemenergy storage. Standard systems: food-protein products, synthetic meat scaffolds. Legionella/ pseudomonas in water system: Community that protects against amoeba. Recycling system for household water - microbiology safety.* <p>Solutions:</p> <ul style="list-style-type: none"> Monitoring. Modify surface to control community. Biochar: Substrate/ matrix to improve adhesion. Better understanding of the community monitoring. 	<ul style="list-style-type: none"> Electrochem: Scale up and decarb. Modelling community behaviours, Omics, monitoring and optimisation, prediction, tools.**** Filtration technology: UV, chemical. 	
C1	<ul style="list-style-type: none"> Standardisation method: e.g. AMR. Robust cheap method. Translation of bench to large scale for measurements.**** 		

Group	What do you see as the opportunities or needs?	What needs to be done to move this forward?	What would it take in time and effort to close gap(s)?
C2	<ul style="list-style-type: none"> Emerging technologies (hyperspatial imaging) application in biofilms.** High throughput experimental platform.**** Collaborative/ multidisciplinary approach.***** Mixed consortia 'biobank' - geographical variables as a resource for researchers. Natural. Better mathematical modelling. Metagenomic database of types of biofilm consortia. In Line monitoring: Metabolites, biosensors, optical sensing. Mixed community bioreactors monitoring.** 	<ul style="list-style-type: none"> Funding. 'Biobank': Set it up! NBIC to facilitate.* Mathematical modelling: PhD maths and biology training. Metagenomic database: Big data AI approach. 	
D1	<p>Surface design</p> <ul style="list-style-type: none"> Generation of components for functional coatings (with proteins?).*** Coatings to promote attachment.* Generation of niche micro environment - microbubbles.***** Micro/ nano scale topology.* Topology and chemistry.* <p>Microbial Community</p> <ul style="list-style-type: none"> Understand the community better*****: Fungi/ bacteria. Protozoa/ algae. Engineer/ modify - with interactions - with genetic modification. En-situ environment testing.*** Phage integration/ individual? <p>Chemical synthetics - mimicking</p> <ul style="list-style-type: none"> Add components to induce a change/ production. Metabolites primary/ secondary products/ use. 	<ul style="list-style-type: none"> Core research, collaborative disciplines, SMEs/ funding. Collaboration: Prevent and Promote come together. Knowledge sharing and industry engagement (What are industry needs?) - workshops like this! Polymicrobial. Interdiscipline: chemistry, physics, biology.* Engage researchers in protozoa/ algae. Advanced modify: mimic environment - O2, carbon source, N2. 	
D2	<ul style="list-style-type: none"> Community indicators/reporter species. Community read-out/ functional indicator. Engineering self-limiting biofilms.** Incremental improvements can have big impacts/ outcomes. Development of a model which will reduce turnaround time.* 	<ul style="list-style-type: none"> More data: What is there and what is it doing?* Understanding inter-species interactions.***** 	

Group	What do you see as the opportunities or needs?	What needs to be done to move this forward?	What would it take in time and effort to close gap(s)?
D3	<ul style="list-style-type: none"> • Bioreactor designs mimicking environments.***** • Water: Low quality water. Saline.* • Maximise efficiency of electricity generation. 	<ul style="list-style-type: none"> • Electricity generation: Optimisation of system (demand of power. Anode/ cathode area and gap, biofilm build up). 	<p>Electricity generation:</p> <p>Engineers, scientific experts etc (5 staff).</p> <p>10 years.</p> <p>£5-6M.</p>
D5	<ul style="list-style-type: none"> • Common overarching goal. • Multi-omics to application. • Intrinsically interdisciplinary: maths, physics etc. • Simulation to predict and explore and optimise.* • Don't let 'the best' be the enemy of the good.* • Opportunities in non-traditional biofilms: Pure with mixed. • Genomics (multi) - applied.* 	<p>Framework, ambition, funds.</p>	<p>Hard problem >>£50k</p>



Appendix 3: Syndicate Outputs

APPENDIX 3.3: BREAKOUT GROUP IDEAS - DELEGATE RATINGS

Ratings	Theme
59	Development and standardisation of experimental and monitoring methods including real-time, high-throughput, large scale and multivariate
33	Model systems including 'good', 'bad', in-situ, en vivo, in vivo, computer. Large and small scale. Cell cultures, human models, nano-materials.
32	Biofilm products.
31	Networking and knowledge exchange. Multidisciplinary collaborative approach to setting objectives, research and targeting funding including
30	Understanding the biofilm: Formation, composition of community, inter-species interactions.
28	Biofilm manipulation including surface, phage, antibiotic, surfaces, self limiting, mixed with algae/fungus, genetic. Prevention.
26	Recycling, waste and value added products including energy and phenolics

Group	Rating (NO. sticky dots received)	Idea	Theme
B2	22	Quick access to industrial setting: To check academic ideas - Petri dish vs biorefiners.	Standardisation of experimental and monitoring methods.
A6	14	Networking opportunities to foster discussions and collaborations on biofilms.	Networking and knowledge exchange.
D2	14	Understanding inter-species interactions.	Understanding the biofilm.
A3	13	Surface manipulation to encourage the right kind of bacteria.	Biofilm manipulation.
A2	12	Stopping 'bad' biofilm growth on collagen sausage casing and in waste water.	Biofilm products.
B1	11	Value added products from waste water.	Recycling, waste and value added products.
D1	10	Understand the community better.	Understanding the biofilm.
A5	9	Fundamental science has to happen but develop new ways to study biofilms. New and more model systems. Move away from laboratory flask (although needed) to cell cultures, human models and nano-materials.	Model systems.
D3	9	Bioreactor designs mimicking environments.	Model systems.

Group	Rating (NO. sticky dots received)	Idea	Theme
A3	7	Change/ manipulate environment to promote a kind of microbiome.	Biofilm manipulation.
A4	7	HT e.g. microfluidic approaches to assess as many variables and create models/ algorithms.	Standardisation of experimental and monitoring methods.
B3	6	Systems for on site recycling of water e.g. domestics.	Recycling, waste and value added products.
D1	5	Generation of niche micro environment - microbubbles.	Biofilm products.
A3	5	Require standardised model systems.	Model systems.
C2	5	Collaborative/ multidisciplinary approach.	Networking and knowledge exchange.
B3	4	Genetic approach to engineer biofilms.	Biofilm manipulation.
C2	4	High throughput experimental platform.	Standardisation of experimental and monitoring methods.
C1	4	Translation of bench to large scale for measurements.	Standardisation of experimental and monitoring methods.
B6	4	Modelling community behaviours, Omics, monitoring and optimisation, prediction, tools.	Standardisation of experimental and monitoring methods.
B4	4	Reliable monitoring - develop models of data.	Model systems.
D1	3	Generation of components for functional coatings (with proteins?).	Biofilm products.
D1	3	In-situ environment testing.	Standardisation of experimental and monitoring methods.
B2	3	Monitoring of consortium over time: AND ability to respond. Biosensors (strains, genetic reporters) embedded within consortium.	Standardisation of experimental and monitoring methods.
A1	3	Understand Your Biofilm Workshop - biophysical course for labs discipline, x - discipline. - Case studies from these. Cross sector UK and others.	Networking and knowledge exchange.
B5	3	Waste treatment e.g. water, litter, feathers, by products.	Recycling, waste and value added products.
A2	2	Design of 'good' biofilm on medical devices instead of engineering clean novel surfaces to stop biofilms.	Biofilm products.
A2	2	Using cellulose as a scaffold for biofilm in different applications? Also chitin can be used or a combination of cellulose and chitin.	Biofilm products.
A6	2	Encapsulating biofilms for internal use in the body.	Biofilm products.
C2	2	Emerging technologies (hyperspatial imaging) application in biofilms.	Standardisation of experimental and monitoring methods.
C2	2	Mixed community bioreactors monitoring.	Standardisation of experimental and monitoring methods.

Group	Rating (NO. sticky dots received)	Idea	Theme
A5	2	Use the different tools and models to bring knowledge together, share knowledge and try and answer key/ big questions - Less money spent in non-useful science.	Networking and knowledge exchange.
D2	2	Engineering self-limiting biofilms.	Networking and knowledge exchange.
B1	2	"Factory thinking" in waste water and energy generation.	Recycling, waste and value added products.
A1	2	Community cultureomics.	Understanding the biofilm.
A3	2	Haven't really demonstrated what a 'healthy' microbiome looks like.	Understanding the biofilm.
A3	1	Manipulate microbial community so that it maintains health.	Biofilm manipulation.
A4	1	Manipulate (or potentially skew ecology) selectively e.g. phage.	Biofilm manipulation.
B3	1	Prevention of biofilms.	Biofilm manipulation.
B5	1	Surface applications for competitive inhibition/exclusion of harmful bugs.	Biofilm manipulation.
A2	1	Can an artificial biofilm restore barrier function in the gut (animal and human)?	Biofilm products.
A6	1	"Cell factory".	Biofilm products.
A6	1	Easily encapsulated: Capsule impermeable to toxins. Capsule is a source of food - degraded, once degraded human immune cells then kill bugs.	Biofilm products.
D1	1	Coatings to promote attachment.	Biofilm products.
B3	1	On site detection systems to find distribution.	Biofilm products.
B5	1	Algal/ fungal/bacterial symbiotic mixed kingdom of biofilms.	Biofilm products.
A2	1	Oceanography technology for gut health models.	Standardisation of experimental and monitoring methods.
A3	1	Reduce inconsistencies between experimental methods.	Standardisation of experimental and monitoring methods.
A4	1	Real time, in-situ measurement - ecology.	Standardisation of experimental and monitoring methods.
A5	1	Robust online measurement for processes: Bacterial growth and transformation. Rapid test, repeatability and safety. Share knowledge and transparency.	Standardisation of experimental and monitoring methods.
D1	1	Micro/ nano scale topology.	Standardisation of experimental and monitoring methods.
D1	1	Topology and chemistry.	Standardisation of experimental and monitoring methods.
D5	1	Genomics (multi) - applied.	Standardisation of experimental and monitoring methods.
A2	1	Standardisation of gut testing techniques.	Model systems.

Group	Rating (NO. sticky dots received)	Idea	Theme
A4	1	Mock (of in-vitro) community predictive of in vivo.	Model systems.
D2	1	Development of a model which will reduce turnaround time.	Model systems.
D5	1	Simulation to predict and explore and optimise.	Model systems.
B3	1	Simulation/use of models to describe microbial biofilms.	Model systems.
A2	1	Technology to allow study of gut in-situ.	Model systems.
A4	1	Investigate what has been done previously and by whom? How successful (and what has been measured).	Networking and knowledge exchange.
A5	1	Spending money in a more targeted manner, more specific towards applications and making sure it is going to bring results/ data/ outcomes.	Networking and knowledge exchange.
D1	1	Interdiscipline: chemistry, physics, biology.	Networking and knowledge exchange.
D2	1	More data: What is there and what is it doing?	Networking and knowledge exchange.
C2	1	Biobank': Set it up! NBIC to facilitate.	Networking and knowledge exchange.
A5	1	Bioindustry waste: Farms, beer, food etc.	Recycling, waste and value added products.
B6	1	Recycling system for household water - microbiology safety.	Recycling, waste and value added products.
B1	1	Commercialisation of phenolics recovery.	Recycling, waste and value added products.
D3	1	Water: Low quality water. Saline.	Recycling, waste and value added products.
A1	1	Move to multi omics.	Standardisation of experimental and monitoring methods.
A5	1	How the biofilms form - identify what make them.	Understanding the biofilm.
B2	1	Natural communities - unknown/competition - bespoke pairwise consortium.	Understanding the biofilm.
D5	1	Don't let 'the best' be the enemy of the good.	

Appendix 4: Companies and Research Institutions registered at the workshop

Abagri	Mira Showers	University of Glasgow
Akzonobel	Moypark	University of Hull
Biocomposites	National Healthcare Photonics Centre	University of Leeds
BMG LABTECH	National Measurement Laboratory	University of Liverpool
Bouygues E&S Contracting UK Limited	P&G	University of Manchester
Carbogénics	Perfectus Biomed	University of Newcastle
Cellucomp	Research Institutions (RIs)	University of Nottingham
Centre for Innovation Excellence in Livestock	Perlemax	University of Sheffield
Department for International Trade	Quadram	University of Southampton
DEVRO	Recircle	University of Surrey
Edinburgh Napier University	Scottish Association for Marine Science	University of York
Graphic Artist	Unilever	
Heriot-Watt University	University of Abertay	
IBIOIC	University of Birmingham	
Imperial College London	University of Canterbury	
Kohler	University of Chester	
KTN	University of Cranfield	
Labtech	University of Edinburgh	
Liverpool John Moores University	University of Exeter	

Thank you

| For further information please contact nbic@biofilms.ac.uk

