Editorial

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Biological wastes and the circular economy: Not yet where we could be

Advanced circular economy solutions for biological wastes undoubtedly merit major efforts in research, development and large-scale deployment. The research landscape in this area is vibrant, and research has a critical role in advancing the state of knowledge regarding high-value conversion of biological wastes, for example through biorefineries. However, there is a notable gap between the solutions favoured by research and their adoption in practice. Innovative circular economy solutions face serious difficulties in making it through the 'valley of death' to get to the market. The 'valley of death' appears to be particularly long and challenging for bio-based solutions. The advanced use of biological waste as a resource in a value-based circular bioeconomy is not yet where the current state of science and research would allow it to be. There is a need to better understand why the circular economy of biological wastes is lagging behind in practice. Positioned at the interface between research and industry in its analysis, the following offers some observations to explore this context.

New waste-related biotechnological solutions need to find their place within established infrastructures, practices and lines of thinking and need to reach out beyond these

From a circular economy perspective, biological wastes are valuable and particularly versatile resources for providing a variety of bio-based products and for supporting innovative bioeconomy businesses that pave the way to a future where society's prosperity is decoupled from the consumption of non-renewable resources, in particular fossil fuels (Chavan et al., 2022; Yaashikaa et al., 2020; Yang et al., 2021). A wealth of innovative ideas has been proposed, and extensive research efforts are exploring new approaches (Ashokkumar et al., 2022; Awasthi et al., 2020; Jain et al., 2022). However, many excellent ideas for high-value valorisation of biological waste are struggling to move beyond the research or prototype scale (Awasthi et al., 2022; Ortega Alvarez et al., 2024; Salvador et al., 2022). The fate of many waste-based solutions is thus no exception in the biotechnological innovation landscape, where the 'valley of death' is particularly long and hard (Kampers et al., 2022; Linton and Xu, 2021). The 'valley of death' refers to the transition between scientific research with technological prototyping at laboratory scale and actual commercialisation in industry. In biotechnology, only a tiny fraction of innovations, estimated at 0.01–0.02% or 1 in 5000 to 10,000, successfully make the long journey from initial discovery to commercialisation (Kampers et al., 2022).

A full overview and systematic analysis of bottlenecks and barriers to market readiness and uptake of circular economy solutions for biological wastes is beyond the scope of this work. The following focuses in an exploratory manner on three main areas of observation to distil useful information from the perspective of the interface between research and industry. This draws insights from the work and discussions carried out within or in relation to the Environmental Biotechnology Network (EBNet, 2024). Funded by UK Research and Innovation, EBNet was set up with the goal of bringing together natural and social scientists and engineers to move discovery science towards practical applications in the creation and optimisation of microbially mediated systems for environmental protection, bioremediation and resource recovery. It consists of over 1300 members from academia, industry and other sectors including public and non-governmental agencies from the United Kingdom and elsewhere. The network operates primarily through working groups set up in response to issues identified by the members. While EBNet finishes in 2025, the Environmental Biotechnology Innovation Centre (EBIC) has been established in 2024 with large-scale governmental funding as a successor organisation and hub to accelerate development of biotechnological environmental solutions (EBIC, 2024).

The three issues presented below may shed light on why adoption of innovative solutions for biological waste valorisation is at best very slow in practice and often does not happen at all and on possible approaches to improve this:

- The biowaste sector already exists and incorporates long-established practices.
- Basic research plays an important role in addressing biological wastes as resources but is often insufficient in itself to be relevant to practice.
- Featuring biological wastes prominently in broader contexts, such as bioeconomy agendas, can unleash urgently needed new dynamics.

Taken together, the observations presented suggest that new waste-related biotechnological solutions need to find their place within established infrastructures, practices and ways of thinking, and that they need to reach out beyond these in order to achieve more widespread acceptance and implementation in practice.

The biowaste sector already exists and incorporates long-established practices

Waste management already has a long tradition, meaning that new solutions must compete with established practices. Changes in practice across the sector have often been a result of regulatory change, rather than pro-active adoption of new technologies. Several reasons may explain why industry across the waste management sector is risk-averse and slow to adopt new ideas and processes, including for biowaste management and valorisation. Waste companies work on long-term contracts and low margins. Infrastructure in the waste and wastewater sector is expensive, long-lived and not very flexible. Capital investment is therefore high, while profits or returns are typically low. In addition, waste management, water supply and wastewater treatment in general are public services. Security of service and public health and safety are major issues, especially for public authorities and in countries with mature economies, so there is little genuine interest and motivation to be first to try something new; and the focus is less on resource recovery optimisation than on safety, security of service and cost. As a consequence, large companies prevail in the sector as established players, offering reliable and well-proven solutions. This creates a challenging context for new approaches and makes it difficult to achieve shifts across the industry and in established practices.

Basic research plays an important role in addressing biological wastes as resources but is often insufficient in itself to be relevant to practice

There is no shortage of science or scientific imagination around waste-based biotechnology, and many very promising ideas and technologies are under investigation (Iragavarapu et al., 2023; Lizundia et al., 2022). Bio-based and bio-degradable plastics and waste-based volatile fatty acids platform biorefineries are only some examples. But despite significant recent investment in R&D and in technology scale-up, for example through the Circular Bio-based Europe Joint Undertaking initiative (Circular Bio-based Europe Joint Undertaking, 2024), there is still a relative lack of successful examples of waste-based biotechnology or waste biorefineries in operation (IEA Bioenergy, 2022). Basic research is fascinating and has high diversity and dynamics but is often undermined by a failure to consider practicability. One issue may be some naivety or over-simplification on the part of researchers. For example, development of plastic-degrading enzymes or polymer-forming microbial cultures may be important steps towards future control of plastic pollution and a fossil-free resource basis, but in practice, most waste streams are at best mixed and often heavily contaminated. It may be possible to achieve changes in social practices that lead to better waste separation at source (Sewak et al., 2021), but it is unrealistic to assume that waste management will ever be dealing with ‘pure’, unmixed or uncontaminated waste streams. Similarly, genetic modification of an organism may confer superior performance in capturing heavy metals or degrading persistent chemicals, but can such an organism survive and operate in the highly competitive environment of a biological treatment plant processing dirty, microbe-rich feedstocks, and if so how can we control its subsequent fate (Sloan and Gómez-Borraz, 2023)? Consequently, solutions that appear to perform well in the laboratory or with ‘clean’ feedstocks may lack usefulness in practice, and waste-based biotechnologies must accept from the start that they will need to deal with contamination of all types.

Many funding agencies now explicitly require direct collaboration between academia and industrial partners, with a view to making academic research more relevant for practice. However, even where cooperation is established, its effectiveness in bridging the ‘valley of death’ is often low. One factor may be that the interests of academia (curiosity-driven) and industry (solution-based) remain fundamentally different in such collaborations (Kampers et al., 2022). Much academic research remains curiosity-driven, often trying to find industrial applications for clever ideas. This may attract industry interest where a proposed solution can be easily integrated into existing practice but is unlikely to encourage industrial uptake of more complex types of solutions, such as advanced biorefineries. When industry initiates research, it is more likely to fund work on immediate problems, which are often localised or driven by short-term regulatory or performance issues. Bridging the interests of academia and industry therefore appears to be a prerequisite for overcoming the ‘valley of death’ for waste-based biotechnological solutions. Co-creation processes in the design of research agendas, arrangements that encourage long-term collaboration between academia and industry beyond single projects and the implementation of schemes that encourage experimentation, for example innovation labs or sandbox models, are some of the measures that can promote this.

Another powerful line of action for tackling the challenges related to slow uptake of innovative waste-based solutions is the use of whole systems approaches that consider the full cycle of biowaste generation and treatment, with integration between all stages to maximise resource recovery and minimise the overall process footprint. While it is clearly neither possible nor desirable to attempt full life cycle assessment (LCA) or life cycle sustainability assessment (LCSA) in the discovery science phase of research, there are major gains to be made from applying whole systems thinking from the start. It can assist in selection and prioritisation of curiosity-driven discovery science topic areas. In a solution-driven context, it can help prevent excessive focus on short-term, bolt-on or end-of-pipe fixes to address immediate issues with conventional technologies. As well as offering a bridge between academia and industry, such thinking brings together the wide range of disciplines and professional backgrounds required to ensure effective translation of waste-based biotechnological innovations through the technology readiness levels from laboratory bench to pilot and demonstration scale,

and across the 'valley of death' to full commercial-scale deployment. Full LCA and LCSA, with their hunger for data and detail, risk adding to the complexity of the process, but a simplified assessment process that carefully tracks a limited set of parameters, including energy consumption/production and mass of key materials, and does not worry so much about some of the more remote or difficult impacts, can provide valuable guidance on where to steer research and development efforts.

Featuring biological wastes prominently in broader contexts, such as bioeconomy agendas, can unleash urgently needed new dynamics

Rather than isolating biological wastes as a sub-topic of waste management, broadening the perspective can be an effective way of promoting waste-related biotechnological innovation. Strategically addressing biological wastes as versatile materials within bioeconomy agendas can generate new dynamics towards high-value valorisation schemes. Anchoring biowaste as a priority issue in the establishment of a regional or local bioeconomy can put an end to the neglect and undervaluing of biowaste as a resource (Kusch-Brandt et al., 2024). This strategy will assign a new role to biowaste – it will no longer be mainly a material to be processed by the waste management sector, but its main role will be to excel as a resource of a region and to support the transition to an economy increasingly based on local and renewable resources. Actions that facilitate the co-creation of solutions by involving different sectors and stakeholders, including public authorities, waste management companies, manufacturing industries, start-ups and research, can then leapfrog standard practices in favour of innovative new solutions.

Another approach to broadening the view of biological wastes and to facilitating a change of mindset around them is to address the valorisation of these materials as an integral part of environmental biotechnology efforts. This allows cross-fertilisation with other disciplines and specialisms, such as industrial biotechnology, bioprocess engineering, enzyme-based biochemistry and other areas of environmental biotechnology, such as wastewater treatment and bioremediation of soils and marine or freshwater water environments. Joining forces across these disciplines and areas will not only facilitate the development of innovative lines of research but will also provide an opportunity to learn effective strategies for overcoming the 'valley of death' on the path to market uptake of biotechnological innovations.

Waste and environmental biotechnology tends to lack glamour as a discipline, so the sector struggles to attract bright students, innovative companies and bold investors (Evans and Furlong, 2011). To accelerate the uptake of innovative schemes for the valorisation of biological wastes, it is essential to effectively bridge disciplines and sectors, reach different audiences and increase the attractiveness of the field. The 'Microbes to the rescue!' short story competition, initiated by EBNet in 2023 as part of the 'Green Stories' initiative, is one example of an unconventional approach to engaging with new audiences, inspiring a change in the perception of environmental biotechnology and showcasing solutions by integrating them into engaging plots. Green Stories, supported by the University of Southampton, aims to contribute to a cultural shift by encouraging writers to embed 'green' solutions in stories for a wide readership, or to create visions of what a sustainable society might look like (Green Stories, 2024). An anthology of selected short stories from the 'Microbes to rescue!' competition is freely available (Byfield and Kusch-Brandt, 2024). One of the authors in the anthology (Ashari, 2024) formulates the position as follows:

> So, if we're gunning for a future that's without a doubt really worth its salt, we gotta change our song. No more crying over spilt milk, it is time to chase after solutions. [. . .] This is real life, with scientists, engineers, and groups coming together to make goals truth. They're turning theories into action, leaving us gob smacked by means of what's viable. (Ashari, 2024)

The bio-based circular economy is a powerful solution approach. Its main goal is to contribute to a society with a sound management of material resources. Innovative ideas that are theoretically feasible but never make it to practical implementation run the risk of being illusions rather than solutions on the way to this goal.

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