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Current and future market applications of genetically modified microorganisms (GMMs) to be placed on the market or for environmental release

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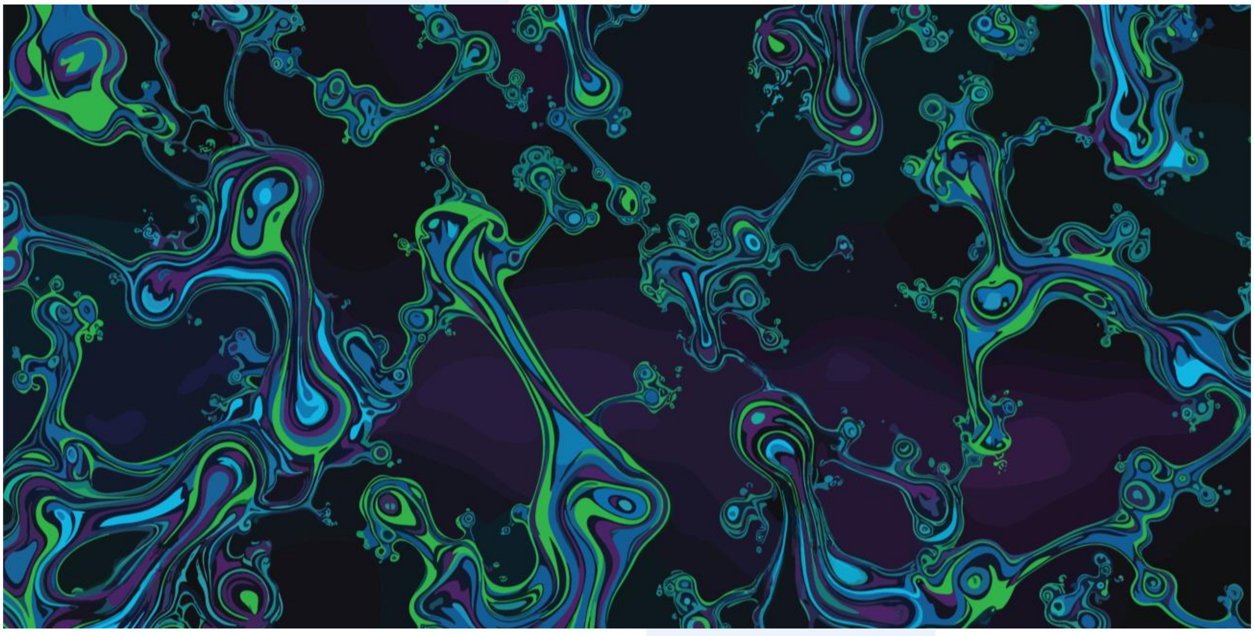

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Contents

Abstract

Genetically modified microorganisms (GMMs) build on a long history of use in industrial processes. With the help of technological advances like gene editing and other new genomic techniques, GMMs are being tailored to surpass the limitations of conventional microbial strains and explore new functionalities. While historically confined to closed systems, activities to expand the use of GMMs to environmental release are growing. Several application areas for GMMs have been identified providing examples of products already commercialised or tested in the field. Out of the 23 startups and scaleups identified as developing GMMs for environmental release, only three were over the age of ten years. The majority were based in the US, with two in the EU. The main application area identified for these startups was agriculture (biofertilisers), with also some activities in biomining (copper-leaching), bioremediation (PFAS remediation), food and beverages (probiotics), and cosmetics and personal care (skin treatments).

In December 2025, the European Commission published a legislative proposal to amend *Directive 2001/18/EC*[1] *as regards the placing on the market of GMMs*, as part of the Biotech Act. This report provides an overview of the technological landscape, sectoral applications, and the scaleup and startup ecosystem around GMMs, excluding healthcare and pharmaceuticals, to feed policy discussions on their safe and scalable deployment in support of the green transition.

1 Directive 2001/18/EC of the European Parliament and of the Council of 12 March 2001 on "the deliberate release into the environment of genetically modified organisms" https://eur-lex.europa.eu/eli/dir/2001/18/oj/eng

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Executive summary

Genetically modified microorganisms (GMMs) represent a key enabling biotechnology, building on a long history of microbial use in fermentation and industrial processes. While the use of conventional microbial strains is limited by their sensitivity to environmental stressors, inconsistent performance, and low productivity, GMMs offer enhanced robustness, efficiency and functionality.

The use of GMMs has historically been constrained to closed systems (e.g., production of pharmaceuticals, industrial biotech). However, recent technological advancements, particularly new genomic techniques (NGTs), together with a growing interest to develop more sustainable alternatives to certain products and practices, are providing an opportunity for GMMs to address several pressing societal challenges through environmental release.

In December 2025, the European Commission published a legislative proposal *amending Directive 2001/18/EC*[2]*, as regards the placing on the market of GMMs*, as part of the Biotech Act. This report explores the technological landscape, sectoral applications, and the scaleup and startup ecosystem around GMMs, excluding healthcare and pharmaceuticals, to feed policy discussions on their safe and scalable deployment to support the green transition.

Key Technological Advances

The pace of technological advances is growing exponentially and is expected to continue to do so in the future. Key advancements relevant for the development of GMMs for target applications, are described below. A major policy challenge is to ensure that legislation can keep pace with scientific developments to foster innovation, while maintaining a high level of safety for human health and the environment.

Gene and whole genome editing techniques are constantly being improved and now include techniques such as base editing, prime editing, and multiplex genome editing (i.e., enabling the targeted modification of multiple genetic sites at the same time). The aim is to overcome early limitations (e.g., off-target effects, limited efficiency in microbial strains) to enhance microbial performance in targeted applications.

Generative artificial intelligence (AI) is accelerating the design of novel proteins, metabolic pathways, and even entire genomes, outpacing natural evolution and unlocking new functionalities.

Biofoundries, integrating robotics, AI, and cloud-based labs[3], are increasingly being used to optimise microbial hosts for industrial-scale production of e.g., biofuels, biomaterials, and fine chemicals.

Genetic circuits (e.g., involving switches) enable "smart" microbes that respond to environmental cues (e.g., pH, pollutants) for self-healing materials, pollution control, and adaptive agriculture.

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2 Directive 2001/18/EC of the European Parliament and of the Council of 12 March 2001 on “the deliberate release into the environment of genetically modified organisms” https://eur-lex.europa.eu/eli/dir/2001/18/oj/eng

3 Cloud-based labs use cloud computing technology to create virtual laboratory environments where users can e.g., perform experiments, training, and simulations, without the need for physical lab space

Sectoral deployment of GMM applications

GMMs targeted towards placing on the market or other environmental release, are starting to penetrate numerous sectors including agriculture, animal feed, biomining, bioremediation, waste treatment and pollution control, cosmetics and personal care, defence, and food and beverages (Table 1). In several cases, GMMs or GMM-containing products have already been commercialised outside the EU or have already undergone field trials.

Table 1. Examples of GMM-containing products that have been commercialised or are undergoing R&D for commercial purposes, with the goal of environmental release or placing on the market.

Application sector	Examples of commercialised or R&D products containing GMMs
Agriculture This sector is the most advanced in the use of GMMs, with several products already on the market for decades. These GMM-containing products function as biopesticides, biofertilisers, biostimulants or protectants from frost damage.	NOGALL (Australia) - GM *Rhizobium rhizogenes* for crown gall prevention (commercialised, 1988).
	Certis USA (US) - GM bioinsecticide *Bacillus thuringiensis* for the control of caterpillars (commercialised, 2003)
	Pivot Bio (US) - GM nitrogen-fixing *Klebsiella variicola* for maize (commercialised, 2019).
Animal Feed There is a growing interest to develop GMM probiotic feed additives, to modulate animal's gut microbiome for increased health and wellbeing.	Folium Science (UK) - GM *Escherichia coli* to eliminate *Salmonella* in poultry (feeding trials, approved in Brazil).
Biomining The interest to leverage GMMs to mine critical minerals and rare earth elements is growing. These compounds, for which the EU is highly reliant on imports, are essential for the green and digital transitions. GMMs can be tailored to overcome the harsh mining conditions that limit the efficiency of native microbes, thereby increasing yield and reducing the costs and environmental impact of the sector.	Endolith (US) - GM microbes for copper heap-leaching (field trials in progress).
	REEgen (US) - GM microbes for rare earth element (REE) recovery from e-waste (R&D).
Bioremediation, Waste Treatment and Pollution Control GMMs can be tailored to degrade specific pollutants (e.g., hydrocarbons, PFAS) and provide a unique and cost-efficient way to remediate contaminated soils or (waste) water.	Lysosome Resources (US) - GM yeast for PFAS remediation (R&D).
Construction Materials The use of GMMs as living biomaterials, or engineered living materials (ELMs), in construction paves the way for a new class of sustainable biomaterials, that can be grown from living organisms or incorporate living cells, to furnish entirely unique capabilities, such as self-healing, carbon sequestration and air pollution filtration.	There is currently a lot of activity leveraging conventional microorganisms, but no information could be found regarding the late-stage development of GMMs for commercial use in the construction sector.

Cosmetics & Personal Care There is a growing interest to develop tailored GMMs for personalised care, focusing on treating skin conditions, ageing and much more.	Lumina Probiotics (US) - GM *Streptococcus mutans* for cavity prevention (commercialised, 2023)
	Synflora (Spain) - GM *Cutibacterium acnes* for the treatment of acne and eczema (preclinical).
Defence Key applications of GMMs include the detection of submarines or explosives in landmines, advanced protective and responsive garments and self-healing materials for camouflage.	Universities in Israel - GM *Escherichia coli* biosensor strain capable of detecting TNT- and DNT-related explosives for the remote detection of anti-personnel mines (tested in field trials).
Food and Beverages While native microorganisms have been used for centuries to produce improved food and beverages, GMMs are being developed as consumer-focused probiotics offering unique health, wellbeing and recreational benefits.	ZBiotics (US) - GM *Bacillus subtilis* for the breakdown of acetaldehyde, the cause of hangovers from drinking alcohol, (commercialised, 2019).
	ZBiotics (US) - GM *Bacillus subtilis* for the conversion of sugar into fibre in the gut (commercialised, 2023).
	Bactose (US) - GM *Lactobacillus acidophilus* for lactose intolerance (commercialised, 2025).
Textiles and Biogarments The use of microbes in biogarmentry, creating living textiles or ELMs, is shifting the fashion industry paradigm from “buy-use-dispose” to “buy-care-compost”. Key developments include air-purifying clothing, algal-based textiles that require no washing and 3D-printed materials that can photosynthesise and self-repair.	There is currently a lot of activity leveraging conventional microorganisms, but no information could be found regarding the late-stage development of GMMs for commercial use in the textile and biogarments sector.

Source: the authors

Startups and scaleups developing or using GMMs

Startups and scaleups are the main drivers of breakthrough innovation. In line with this, most of the GMM products identified in this report and which have recently received market authorisation for release, were developed by startups. This includes ZBiotics’ GM probiotics to treat hangovers and increase fibre in the gut, Pivot Bio’s GM nitrogen-fixing biofertilisers and Lumina Probiotic’s GM cavity-prevention probiotic.

The authors identified 309 startups and scaleups currently developing and/or using GMMs or GMM-containing products, excluding the health and pharmaceutical sector. This number is likely underrepresenting the sector, as many relevant companies do not explicitly mention the use of GMMs in their activities, especially for companies using GMMs in closed systems. Despite this limitation, the analysis provides a value for the magnitude of startups/scaleups operating in this field and targeting environmental release or placing on the market of their GMMs, compared to those limiting their activities to closed systems.

Out of these 309 startups/scaleups identified, 23 were confirmed as developing and/or using GMMs specifically for environmental release, or potentially for both release and contained use. Interestingly only three of these firms were over ten years old, confirming that this is an emerging field. The main application sector was agriculture, with eight companies operating in this field (~35%). This is followed by biomining (3, 13%); bioremediation, waste treatment and pollution control (3, 13%); food and beverages (3, 13%); animal feed (2, 8.7%), cosmetics and personal care (2, 8.7%) and services (2, 8.7%). The majority of the companies (15) were based in the US, while only two companies were located in the EU (one in Denmark and one in Spain). The remaining companies were based in Brazil (3), the UK (2) and Israel (1).

The US-based firms represented all the firms operating in biomining, bioremediation, and food and beverages, and the majority of those (4 out of 7) targeting the agricultural sector. It is worth noting that all three US-based startups in the biomining sector were founded 3-4 years ago, with two of them describing their mission as ensuring the US's energy security and reducing reliance on third countries.

Conclusions

Microbes already play an essential role in numerous key sectors. As part of the green transition, additional sectors are looking to microorganisms to provide more sustainable solutions to current challenges and practices. A large proportion of commercial GMM-containing products for environmental release were launched in recent years, and it is expected that we will see GMMs transition from closed systems and niche applications to more large-scale environmental deployment over the next decade. This expectation is further supported by the speed of technological advances, particularly of gene editing technologies, in combination with automation, AI and machine learning (ML).

The agricultural sector appears as the main target for GMM-derived innovations with the reduction of synthetic inputs and resilience to environmental stress the main objective. The development of GMMs for sectors such as bioremediation and biomining, offers novel solutions to address major environmental challenges, where conventional microbes have often failed to provide cost-efficient results. The high proportion of young startups working in this area suggests that this is an emerging field that will increase in the coming years, with currently the US leading the way.

1. Introduction

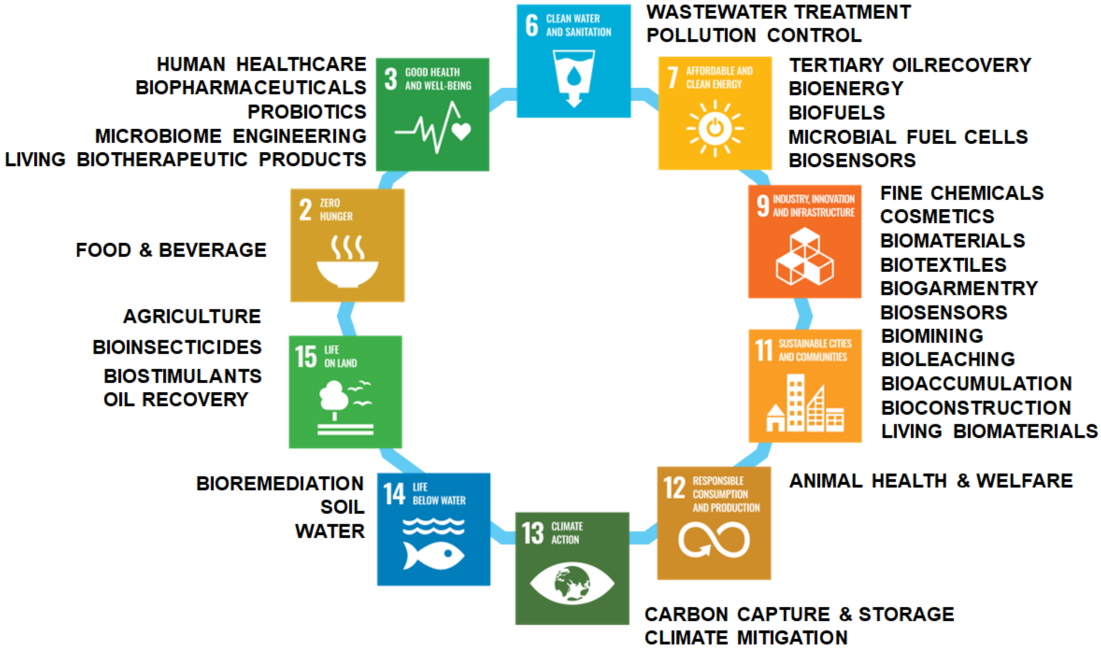
The use of microorganisms by humans can be traced back thousands of years to ancient civilisations that exploited fermentation systems to create bread, beer, yogurt, cheese and vinegar. Major scientific advances in the last century, particularly in areas like microbiology, genetics and biotechnology, have enabled the application of microorganisms, or microbes, to address challenges across a wide range of sectors. Despite this, limitations exist when using conventional microbial strains, as they are sensitive to external factors including pH, temperature and the nutrient content of the growth environment. In addition, they often do not provide sufficient consistency, quality and productivity to make their use reliable and cost-effective for commercial use. Efforts to improve microbial strain performance through conventional methods are complex, time consuming and limited in scope. On the other hand, the use of genetic modification through traditional transgenesis, or NGTs, has enabled the tailoring of microbial strains for broad deployment in industrial biotechnology, to produce, for example, chemical compounds or food and feed ingredients.

All living organisms – animals, plants and microorganisms – can be genetically modified, but where the recipient is a microorganism, they are typically referred to as genetically modified microorganisms (GMMs). These GMMs have ushered in a new era in our ability to address the needs of a growing and changing world (Cohen and Chang, 1973). The term microorganism is not well defined but is generally attributed to small living organisms smaller than 200 µm or which can only be seen using a microscope (Sanz, 2011).

The small size, short generation times and relative ease of genetic manipulation of microorganisms, particularly using advanced technologies to enhance natural biological functions or adding new ones, has been transformational in creating new and improved products and processes across medical, agricultural, environmental, food and beverages manufacturing and other industrial sectors. Such developments can contribute to many of the United Nation's Sustainable Development Goals (SDG) by diminishing hunger (SDG2), improving health and wellbeing (SDG2), providing clean water and sanitation (SDG6), moving towards affordable and clean energy (SDG7), promoting green industries (SDG9), sustainable urbanisation (SDG11) and natural resources (SDG12), mitigating climate change (SDG13), marine pollution (SDG14) and land degradation (SDG15)[4]. Figure 1 shows the relationship between the SDGs and the use of GMMs.

[4] United Nations: Transforming our world: the 2030 Agenda for Sustainable Development. http://sdgs.un.org

Figure 1. Relationship between UN Sustainable Development Goals (SDGs) and applications of genetically modified microorganisms (GMMs).



Source: Adapted from UN Sustainable Development Goals (2026) by the authors

With some exceptions in agriculture, applications using GMMs have mostly been limited to uses in closed systems. However, there is now a growing trend to leverage GMMs for applications involving environmental release, with several products having been commercialised in the last years. In addition, the advent of NGTs or new breeding techniques (NBTs), such as gene editing, has led to many countries (e.g., Argentina[5] and Brazil[6]) updating their legislative frameworks to ensure more proportionate assessment of plants, animals and/or microorganisms developed using these methods[7]. Updates range from the exclusion of NBT/NGT organisms from provisions for genetically modified organisms (GMOs) (most often if no foreign DNA has been inserted), to a simplified GMO authorisation process. Additional countries are either in the process of updating their legislation or assessing how to best update it. Interestingly, some countries have chosen to restrict the scope of their legislative update to specific organisms (e.g., the EU's Regulation (EU) 2026/1388[8] only addresses plants, England's Precision Breeding Bill[9] only addresses plants and animals), while other countries, notably Argentina and Brazil, have kept all organisms in scope. As a result, the global shift towards reducing the regulatory barrier for authorisation of organisms developed using NGTs, has not equally addressed microorganisms in all jurisdictions. The result is that, in some cases, the

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5 Resolution No. 24/2026 - Nuevas Técnicas de Mejoramiento (NBT)

6 Resolução Normativa Nº 16, de 15 de janeiro de 2018 - sobre as Técnicas Inovadoras de Melhoramento de Precisão

7 Website: Global Gene Editing Regulation Tracker and Index

8 Regulation (EU) 2026/1388 of the European Parliament and of the Council of 17 June 2026 on plants obtained by certain new genomic techniques and their products, and amending Regulation (EU) 2017/625 *OJ L, 2026/1388, 26.6.2026, ELI:* *http://data.europa.eu/eli/reg/2026/1388/oj*

9 Genetic Technology (Precision Breeding) Act 2023 - Government Bill

same microbe-containing product could be regulated as a GMM in the EU, while being considered a conventional product in other jurisdictions.

The EU's legal framework for GMOs, which include GMMs, was put into place in the late 1990s and was developed with genetically modified (GM) plants in mind. It is therefore less suitable to address the specificities of GMMs and their applications. With that in mind the European Commission proposed, in December 2025, to amend Directive 2001/18/EC as regards the placing on the market of GMMs, as part of the Biotech Act I.

This report aims to feed the political discussions by providing an overview of the technological state-of-the-art and emerging technologies relevant for the development and use of GMMs, as well as the principal areas of application of GMMs intended for environmental release, including placing on the market. Where available, examples of GMMs under research and development (R&D) or already commercialised, are described, as well as startups and scaleups working in this space. The scope of the report covers all main application areas, except health and pharmaceuticals.

2. Technological Landscape

Microorganisms possess a wide repertoire of metabolic capabilities that allow them to thrive in diverse and changing environments. The underlying genes determining these capabilities can be altered to modify their characteristics in a pre-determined way to create GMMs. For example, *Escherichia coli* (*E. coli*) bacteria were first genetically modified to produce human insulin in 1978 (Goeddel et al, 1979). Genetic modification has progressed substantially since the 1970's and it is now possible to rewire entire metabolic and regulatory frameworks to introduce enhanced or new functionalities that improve microbes' utility in applications of benefit to humanity or the environment (Jones et al, 2024).

2.1. Current and emerging tools for genetic modification

Genetic modification is the process of using laboratory tools to change the nucleic acid sequence of a microorganism by removing or adding base pairs, inserting or inactivating a gene, thereby creating a new characteristic in a GMM. Historically, the genetic modification of microbes was mostly done through a method called transformation (Han, 2004). In this process, recipient microorganisms are exposed to target DNA sequences under specific conditions, promoting the uptake of the DNA, similar to the natural process of horizontal gene transfer. In such cases, researchers could not always predict the outcome of the genetic modification, or where in the genome of the microorganism, an inserted gene would end up. Now, there are more specific gene editing tools, which mimic native repair mechanisms, or can be used for targeted insertions of nucleic acids or edits in the genome.

Genome editing, or gene editing, is a precise type of NGT that uses molecular tools to insert, delete or replace DNA in the genomes of living organisms. The discovery and development of genome editing tools have been transformative for the life sciences, owing to their simplicity of programming, specificity and versatility (Komor et al, 2017; Shivram et al, 2021; Pacesa et al, 2024). The pre-eminent tool, Clustered Regularly Interspaced Short Palindromic Repeats (CRISPR), in association with CRISPR-associated nuclease 9 (Cas9) (CRISPR-Cas9 systems) is directed by a guide RNA (gRNA) which is complementary to, and cleaves, the target DNA, mirroring the natural process of adaptive immunity in bacteria (Liang et al, 2025). While groundbreaking, the application potential of first generation CRISPR-based genome editing tools, based on the Cas9 nuclease, has been limited by specificity, off-target activity, targeting scope and the requirement to depend on innate double-strand break repair to achieve genome edits. Novel approaches such as the use of newer CRISPR nucleases, Base editing, Prime editing, Multiplex genome editing , Retron library recombineering and Oligo Recombineering followed by Bxb-1 Integrase Targeting have addressed these constraints and improved the efficacy and versatility of genome editing. This has addressed many of the specific challenges posed by different microorganisms and industrial applications, particularly in high-value chemical synthesis, food, biofuels and bioremediation (Table 2) (Dudeja et al, 2025).

Sidewinder is a newly introduced DNA construction tool which allows the affordable compilation of large and complex synthetic DNA sequences. This was previously limited by DNA synthesis via conventional chemistry (that produced only a few hundred bases) and enzymatic joining technologies, to assemble these short oligos. To date, those used by nature or mankind rely on two-way junctions between two complementary strands of DNA. Sidewinder uses three-way junctions, which can be used reliably to construct DNA of any sequence or length, with a misconnection rate of only ~1 in 10^6 nucleotides. This new approach offers for the first time the possibility to stitch together any number of DNA oligonucleotides, 10-1000s times longer than current capabilities allow, to create a much larger piece of DNA, up to the scale of a complete gene or, potentially, an entire genome (Robinson et al, 2026). This innovation clears a major bottleneck for bioengineering new compounds and materials, and it could have a vast array of applications, including in medicine, agriculture, materials science and other bioengineering applications.

Table 2. Summary of the advantages and disadvantages of different emerging NGTs.

Editing tools	Advantages	Disadvantages
CRISPR-Cas9[1]	High efficiency & simplicity Cost-effective Precise targeting Versatility	Off-target effects Delivery limitations Mosaicism (Not all cells edited) Immunogenicity
Base Editing[2]	High precision & efficiency No double-strand breaks Fewer unwanted insertions or deletions Applicable to non-dividing cells Reduced cellular toxicity	Off-target effects Restricted to point mutations Limited range of conversions (Primarily limited to C) Bystander editing if multiple Cs Limited target scope
Prime Editing[3]	High precision & versatility No double-strand breaks No donor template needed High target specificity Works with dividing/non-dividing cells	Low editing efficiency Prime editor protein is large Complex design Long-term effects unknown
Multiplex Genome Editing[4]	Time and resource efficiency Simultaneous targeting Rapid production of mutants Application versatility Improved off-target performance Effective in polyploids	Increased risk of off-target effects Reduced efficiency with increasing targets Unintended genomic rearrangements Complex design and construction Large construct sizes Mosaicism (uneven editing) Bystander effects
Retron Library Recombineering[8]	No double-strand breaks High throughput and multiplexing *In vivo* DNA generation In-built barcoding High precision and efficiency Continuous evolution capability	Limited to actively dividing cells Low efficiency in non-model organisms Limited editing size Complex cloning process Lower efficacy in eukaryotes Requirement for optimised strains
Oligonucleotide Recombineering[5]	High precision and Efficiency Simple and cost-effective Low homology requirements Broad applicability Multiplexing potential Independent of host machinery	Limited to short DNA modifications Low frequency in non-model organisms Lack of selection/screening required Off-target effects
Oligo Recombineering with Bxb1 Integrase Targeting[6]	Kilobase-scale modifications High efficiency “Drag and drop” versatility Single transformation High-throughput large libraries No double-strand breaks	Requires strain engineering Bxb1 inserts specific sequence: Leaves “scar” Restricted to specific bacteria Requires specialised plasmids

Sidewinder[7-9]	AI-informed DNA construction tool Builds long and complex DNA sequences High accuracy and low error rates Enables rapid and automated construction of genes, cluster and genomes Can create combinatorial libraries Widely applicable	Emerging technology Potential technical hurdles High throughput technologies expensive Regulatory and safety concerns

1 Komor et al, 2017; Shivram et al, 2021; Pacesa et al, 2024; Liang et al, 2025
2 Sichani et al, 2023
3 Lu et al, 2022
4 Abdelrahman et al, 2021
5 Kaur and Pati, 2024
6 Sun et al, 2023; Saunders and Ahmed, 2024
7 Robinson et al, 2026; Spencer, 2026
8 Caltech Press Release (2026) Invention of DNA "Page Numbers" Opens Up Vast Possibilities for the Bioeconomy
9 Press Release (2026) Genyro Signs Exclusive License for “Sidewinder,” a Breakthrough DNA Construction Technology Featured in Nature

Source: the authors

2.2. Artificial Intelligence (AI) and Generative Biology

AI models have been developed to assist genome editing to achieve more precise, efficient and cost-effective edits, whilst improving the design of gRNA to minimise off-target effects (Dixit et al, 2024).

Generative AI is transforming how biologists comprehend living systems, by advancing modern computational biology and moving from static predictions to active design and exploration (Li et al, 2026). In computational science, advanced models, such as large language models (LLMs) and diffusion models, are beginning to reshape workflows for analysis, synthesis and interaction and, thereby, create a new paradigm of generative biology.

Generative AI is already being used for *de novo* design of genomic elements and synthetic genomes (King et al, 2025,[10]). The technology outperforms nature by designing new and more performant synthetic proteins for genome editing. It can also predict how different DNA sequences behave in various cellular environments, effectively modelling the outcomes of future experiments, and can create new mRNA sequences, with significantly increased stability and translational efficiency. Generative AI can predict the impact of mutations on protein expression levels and cellular functions and is thus heading towards the creation of bespoke sequences for a variety of applications.

Recent advances in generative biology are beginning to create entirely synthetic strains and species by shifting the paradigm from "rational design" to autonomous, AI-driven generation of novel biological functions (Manan et al, 2025; Liu, 2025). For example, key developments include the AI-driven design of novel genetic parts, protein engineering, *de novo* sequence creation for optimising microbial strains for industrial biotech, creating minimal genomes for host organisms (Sleator, 2016), improved genome editing via CRISPR-Cas9 systems and synthetic pathways being ported across kingdom boundaries, for example, plant pathways into yeast or *E. coli,* to produce high value

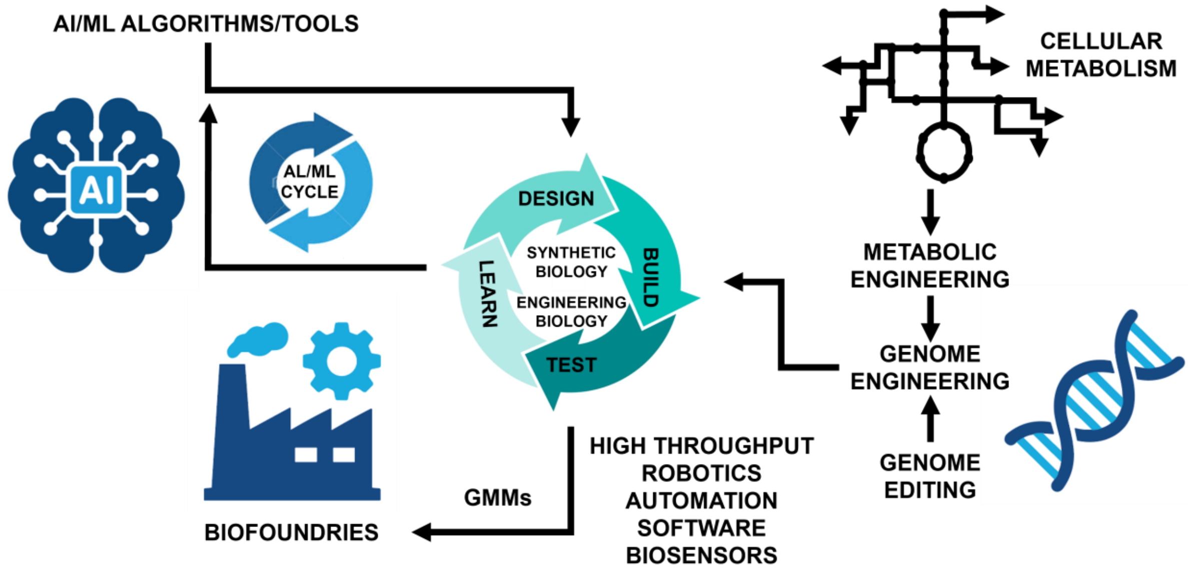
[10] Welcome News - Chin J (2025) Researchers take first steps to creating synthetic human genomes.

products, like bioactive compounds (Liu et al, 2026). These approaches exploit automated robotic biofoundries, which integrate the "design-build-test-learn" (DBTL) cycle to enable high-throughput synthesis and testing of thousands of genetic variants, thereby accelerating development from years to months. They also leverage techniques for engineering new host organisms, with artificial scaffolds and bespoke promoters to improve metabolite yields.

2.3. Synthetic Biology/Engineering Biology

Synthetic biology and engineering biology are two distinct terms with some overlap and complementarity (Clarke, 2020). Synthetic biology has evolved from a better understanding of the building blocks of life, particularly our ability to 'read' and 'write' DNA and to predict and control its function within organisms, while engineering biology tends to refer to the application of engineering principles to biology, by designing, re-engineering, or building novel biological systems, such as microorganisms, cells, or proteins for the production of e.g., fine chemicals, biomaterials, biofuels and medicines. The latter is built upon modular design principles, computational modelling and artificial intelligence (AI) to fabricate predictable and scalable genetic circuits for specific functions via the DBTL cycle (Figure 2).

Figure 2. A simplified view of modern tools for the creation of GMMs



Source: the authors

Unlike traditional labour-intensive methodologies, these new techniques offer rational engineering of microorganisms. New developments in genome editing, metabolic pathway engineering and synthetic regulatory networks, have resulted in improved GM strains, with significantly advanced microbial productivity and robustness. Coupled with machine learning (ML), high-throughput screening, robotics and automated biofoundries, these tools are capable of increasing yields at scale in GM strains employed in various industrial processes (Jeong, 2025).

2.4. Metabolic Engineering

Metabolic engineering seeks to enhance microbial productivity by modifying specific biochemical reactions or sequences through genetic modification. Early attempts at metabolic engineering relied on rational numerical approaches to pathway analysis and flux optimisation, to regulate cellular metabolism and redirect flux to the desired commercial products. Improvements in metabolic engineering in the 2000s extended the approach to genome-scale models and genotype-phenotype relationships, to create a holistic understanding of the metabolic potential of the microbial cell factory. Now, complete metabolic pathways are being designed, constructed and optimised using synthetic nucleic acid elements, to produce both natural/non-natural and inherent/non-inherent products, including fine and commodity chemicals, biofuels, pharmaceuticals, nutraceuticals, opioids, alkaloids and non-natural amino acids (Chai , 2025).

2.5. High-Throughput Automation and Biofoundries

Engineering biology aims to meet the challenges of biomanufacturing by creating strains that are technically and economically feasible. This involves navigating extensive combinatorial design spaces, by selecting starting materials, host strains, biosynthetic routes; optimising enzyme activities, gene expression, codons, genomic integration and media; and considering carbon metabolism, redox balance, process scaleup and downstream separation processes (Petzold and Mukhopadhyay, 2025). Advanced AI and ML design methods, data-driven models, genome-scale metabolic models and protein structure software, such as AlphaFold 3.0, serve to navigate the design space more effectively. Robotic automation and software have revolutionised DNA assembly, strain optimisation, cell cultivation and high-throughput screening. Automating tasks involved in the DBTL cycle such as cell transformation, cultivation and harvesting, reduces errors and improves reproducibility. However, despite these advances, additional challenges need to be overcome to fully realise the potential of automation, including the lack of standardisation of protocols and interoperability among different platforms and software.

The use of robotics in synthetic biology supplements “wet-lab”[11] work, eases data management and paves the way for cloud labs and biofoundries, such as iBiofab (HamediRad et al, 2019). Cloud labs allow scientists to conduct experiments remotely through robotic systems, but are not suitable for all types of research, particularly those requiring specialist equipment unavailable within the cloud lab infrastructure. Biofoundries function as integrated facilities focused on the automated DBTL cycle for modifying organisms and exploiting robotic platforms and advanced software tools. They are particularly appropriate for genome editing, the development of novel host organisms, systems-level work and omics assays, which can lead to rapid prototyping and novel biomanufacturing solutions. ML-algorithms can enhance data-driven “learn” approaches, to predict enzyme functionality, directed evolution and metabolic pathways (Yu et al, 2025). However, it is worth recalling that a biofoundry requires more than equipping a building with high-throughput infrastructure. It also necessitates integrating computing power and software, liquid handling capability, high-throughput analytical instrumentation, highly skilled personnel at all levels and data storage and analysis.

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[11] A wet lab is a type of laboratory in which a wide range of experiments are performed, for example, characterising of enzymes in biology, titration in chemistry, diffraction of light in physics, etc.

2.6. Future Applications

The ability to manipulate and/or create entirely new functionalities in GMMs, opens up many possibilities to deliver on the needs of industry and society, while mitigating many of the most pressing humanitarian and environmental challenges.

One forward looking application involves ‘genetic circuits’. These are devices that sense inputs and generate outputs. They can remember, integrate or amplify signals and serve as the basis for more complex networks, enabling control at multiple levels of gene expression (Müller et al, 2025). Such devices can act on DNA sequences and regulate epigenetics, transcription, translation and post-translational modification via a variety of routes. Genetic circuit design aims to incorporate quantitative engineering principles to create robust, tuneable and predictable biological systems, from reliable components. The key principles of modularisation (independent, interchangeable parts), standardisation (interoperability), orthogonality (components operating independently without interfering with each other), tunability (adjustable components) and robustness (reliable components), enable the development of increasingly sophisticated genetic networks. Standardised modular genetic circuits allow proponents to combine sensors, signal processors and actuators, to develop bespoke circuits in a “plug-and-play” mode. Machine learning and computational tools are being applied to predict the behaviour of genetic units and complex circuits. These developments are particularly relevant to industrial biotechnology and have enabled a more dynamic control over gene expression and metabolic flux, optimising feedstock utilisation, reducing toxicity and metabolic burden and, thereby, increasing yields and improving robustness.

The emergence of “lab-in-the-loop” biological models, such as the DBTL cycle, in which molecular design, experimental testing and model retraining occur in continuous fully automated cycles, and are likely to be transformative for the creation of novel GMMs. The self-reinforcing nature of these cycles could result in productivity gains by eliminating the current bottleneck of wet-lab experimentation and by translating computational designs into novel biological systems.

3. The deployment of GMMs across sectors

The human and animal healthcare sector has previously been the preeminent user of GMMs for producing novel drugs, innovative therapies and diagnostics (Cohen and Chang, 1973). In more traditional sectors, such as food and agriculture, GMMs are now transforming how food is produced (precision fermentation, novel flavourings and sweeteners, biofertilisers, biostimulants, processing aids) and how crops are protected (biopesticides, protection against freezing) (Hanlon and Sewalt, 2021; Gari et al, 2023). Furthermore, GMMs are creating a focus on sustainable "green" industry (biochemicals, biodegradable polymers, biofuels, biomaterials) (Mirsalami and Mirsalami, 2025; Chaudhary et al, 2025), sustainable resource recovery (biomining, bioleaching and bioaccumulation) (Yaw Owusu-Fordjour and Yang, 2023) and bioremediation of soil and water from e.g., toxic industrial chemicals and heavy metals (Singh et al, 2021). There is a current shift in focus for modifying microorganisms using advanced molecular biology technologies, from the production of small-scale, high-value products for e.g., fine chemicals or enzymes, to the production of large-scale commodity products for e.g., agriculture, biomining and bioremediation.

The following sections outline the main applications and sectors that are already exploiting, or are likely to exploit GMMs, excluding healthcare and pharmaceuticals.

3.1. Agriculture

Native microorganisms with pre-existing evolutionary relationships to crops have been used for many years in agriculture to shield crops from pests, pathogens and frost, or to improve yields. Many free-living soil microorganisms that form colonies close to roots, help to regulate soil fertility and nutrient recycling, maintain plant diversity, fortify plants against biotic and abiotic stresses and offer potential solutions to the current challenges facing agriculture (Zhyr et al, 2026). These beneficial microorganisms, mostly bacteria and fungi, are being integrated into seed delivery technologies, i.e. coating seeds with protective binders, to act as biostimulants and thereby improve nutrient utilisation, germination, plant health and resilience against stress. These technologies allow for more sustainable practices by reducing chemical inputs and increasing crop resilience in changing climates (Matilla, 2025).

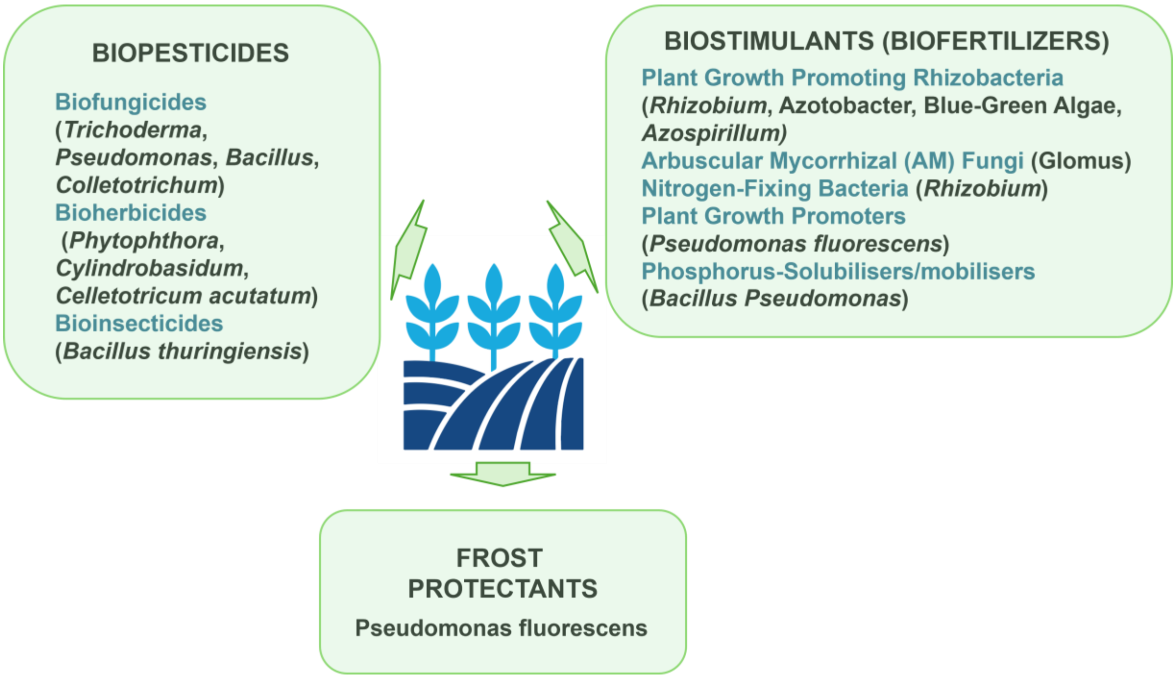
In particular, bioinoculants such as rhizobia have long been used to modulate crop-associated microbiomes to enhance plant and crop productivity in legumes, and were one of the first microbes to be genetically modified to optimise legume-rhizobia interactions for higher performance (Hirsch, 2005). The last decades have seen substantial effort being extended to design and apply biofertilisers, mainly aimed at enhancing nitrogen use efficiency in non-legume crops (Figure 3). Such biofertilisers have been shown to function well in diverse soils, climates and crop systems (Amarger, 2002). One example includes the GMM-containing PROVEN® 40 product that was commercialised by startup Pivot Bio[12] in the US in 2021 (following the market entry of its first generation PROVEN® in 2019). Designed for maize, it has been demonstrated to maintain yield with lower nitrogen (N)-input and increase yield and performance under sustained N-input (Woodward et al, 2025; Wen et al, 2021; Burren et al, 2026). Ongoing activities include the adaptation of the PROVEN® products for use with cotton, wheat and sorghum. Several other companies are

[12] Company website: https://www.pivotbio.com/

developing N-fixing GMMs, including US startups Bioconsortia[13], Switch Bioworks[14] and Joyn Bio[15]. The latter being a joint venture between Ginkgo Bioworks and Leaps by Bayer. At present, to our knowledge no other GM biofertilisers have been commercialised, besides Pivot Bio's PROVEN® series.

In addition to biofertilisers, other types of biostimulants aim to enhance plant growth, nutrient uptake, stress tolerance, and overall crop quality by stimulating natural plant and soil processes, rather than supplying nutrients directly. One example includes the gene edited *Bacillus thuringiensis israelenses* being developed by BASF. When applied to the seed coating, the GMM is programmed to release cellulases upon soaking. The cellulases act to degrade the organic matter around the plant roots, resulting in greater availability and absorption of nutrients (Miklau et al, 2024). While a preliminary decision in 2021 by Brazil's National Technical Biosafety Commission (CTNBio) ruled the GMM as non-GM (under Brazil's new breeding technique framework RN16), this product has yet to reach the market. In addition to this example, the UK startup CroBio[16] is also developing biostimulants, including root-associated GMMs capable of excreting cellulose to retain water in the soil, thereby reducing the need for irrigation and increasing drought resilience. In a patent claim filed in the US, the developer states that its product can also increase carbon sequestration in the soil and improve soil fertility[17]. However, no known product has been commercialised yet.

Figure 3. Applications of microorganisms in agriculture



Source: the authors

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13 Company website: https://bioconsortia.com/

14 Company website: https://www.switchbioworks.com/

15 Company website: https://leaps.bayer.com/companies/agriculture/joyn-bio

16 Company website: https://www.crobio.com/

17 Patent data https://patents.justia.com/patent/20230034438

Microbial pesticides, or biopesticides, can originate from native or GM bacteria, fungi, algae, viruses or protozoans, and include biofungicides and bioinsecticides. They can discourage pests via a diverse range of strategies, including toxic metabolites, endotoxins, disease, competitive exclusion and other modes of operation depending on the specific microorganism (Meadows , 1992). Bacterial biopesticides are the most widely used and require direct contact with their target to be effective. *Bacillus thuringiensis* (*Bt*) is the most widely applied biopesticide used for over the past nine decades for the control of corn and cotton damage caused by insects (Li et al, 2024). A GM strain of *Bt*, contains toxins from both *Bt kurstaki* and *Bt aizawai* and was commercialised as a biopesticide by Certis USA[18] in 2003. To our knowledge, no ill effects specifically related to the release of this GM strain have been reported. Bt-toxin genes have also been engineered into several root colonisers, symbiotic bacteria and endophytic bacteria (Azizoglu et al, 2023).

Another GMM-containing product, NOGALL, provided by Australian company Bio-Care Technology[19], was approved as a biopesticide and launched in its home country in 1988, and later expanded to other countries, including the USA (2000) and Türkiye (2005). NOGALL contains a modified strain of *Rhizobium rhizogenes* (formerly *Agrobacterium radiobacter*), which provides protection from crown gall through the production of an antibiotic compound (Kerr and Bullard, 2020). Crown gall is caused by soil-inhabiting bacteria that transfer some of their DNA to the cells of fruit trees, triggering uncontrolled cell growth resulting in galls or tumours. Since the genetic modification of the bacterial strain only involves the deletion of a small portion of DNA, it is not considered a GMM in many countries (Kerr and Bullard, 2020)[20].

In the 1980s and 90s, the company Mycogen Corporation developed, field trialled and commercialised multiple GMM-containing bioinsecticides in the US, based on modified *Pseudomonas fluorescens* strains, named MCap™ MVP®b, and M-Press®, expressing different proteins from *Bt*.: (Supp info in Chemla et al, 2025)[21].

Some microbial strains belonging to the genera *Pseudomonas*, *Xanthomonas* and *Erwinia* contribute to frost damage by initiating the formation of ice in plants (Dar et al, 1993). Inoculation with GMMs, in which the genes conferring ice nucleation were deleted, proved effective in controlling frost injury in greenhouses and field trials, with potatoes, pear trees and flowers (Lindow and Panopoulos, 1988; Chemla et al, 2025). In field trials the GMMs reduced frost injury to plants, while not surviving in soil and not showing aerial dispersal in the environment. Despite the research and successful field trials dating back to the 1980s, the product was never commercialised. Suggested reasons for this include "*protracted regulatory process thwarted commercialisation* (Supp info in Chemla et al, 2025)".

In addition to improving crop performance and supporting more sustainable agricultural practices, GMMs are also being developed to increase food safety, particularly when crops are grown on contaminated sites or on sites where natural toxic compounds can be found in high concentrations. For examples, arsenic (As) is a naturally occurring metalloid that can accumulate in soils and groundwater and is a major global health issue, particularly in South and East Asia (Kaur et al,

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18 Company website: Crymax - Bioinsecticide - Certis Biologicals

19 Company website: https://bio-caretechnology.com/nogall-biological-control-treatment/

20 USA Environmental Agency (EPA) Technical Document (006474) Agrobacterium radiobacter strain K1026

21 The company has since undergone several rounds of acquisition and it is currently unclear whether these products are still commercially available. Mycogen Corporation -- Company History

2025). Crops grown on As-rich soils or irrigated with As-contaminated groundwater show loweris the performance and accumulate As in their tissues. The latter is most concerning as it introduces As into food systems. GMMs aimed at reducing As content of agricultural soils or groundwater are therefore being developed. These products include GM strains of *Pseudomonas putida* and *Pseudomonas aeruginosa*, that reduce As accumulation in root tissues and enhance plant growth (Patel et al, 2024).

Table 3. Examples of GMM-containing products for applications in agriculture. For a more exhaustive list of global field trials, including outcomes, see the supp. Info. (Chemla et al, 2025).

Microorganism	Purpose	Developmental Stage
Bacteria (*Bacillus thuringiensis* strain EG7841)	GMM bioinsecticide for the control of caterpillars[1]	Commercialised in the US (EPA approval in 2003) Certis USA
Bacteria (*Rhizobium rhizogenes*, formerly *Agrobacterium radiobacter* K1026)	GMM biopesticide preventing crown root gall in fruit trees through the production of an antibiotic compound[2,3,4]	Commercialised in Australia (1988), the US (2000) and Türkiye (2005) Bio-Care Technology
Bacteria (*Klebsiella variicola* Strain KV137, *Kosakonia sacchari* Strain Ks6-5687)	N-fixing GMMs as biofertiliser[5]	Commercialised in 2019 in the US Pivot Bio
Bacteria (*Bacillus polymyxa* and *Bacillus odorifer*)	N-fixing GMMs as biofertiliser[6]	R&D. Approved for field trials in Brazil in 2023[7] Bioconsortia
Bacteria (*Bacillus thuringiensis israelenses*)	GMM biostimulant that produce cellulases to enable better availability and absorption of nutrients[8]	R&D. Not considered GMO under Brazil's 'new breeding technique' framework RN16" (preliminary decision 2021)[9] BASF
Bacteria (*Pseudomonas fluorescens, Acetobacter, Sarcina ventriculi and Agrobacterium)*)	Root-associated GMMs that excretes water-retaining cellulose around plant roots thereby providing protection from drought[10,11]	R&D in the UK CroBio
Bacteria (*Pseudomonas Syringae*)	GMM conferring resistance to frost damage to plants[12]	R&D Efficacious in field in the US. Received Biotech notification (1985 and 1987) and registered (1992) under FIFRA.
Bacteria (*Pseudomonas putida* and *Pseudomonas aeruginosa*)	GMMs able to reduce the accumulation of Arsenic in plant roots and improve performance[13]	Research with field trials in India

1 Company website: https://www.certisbio.com/products/bt-biolarvicides/crymax
2 Company website: https://bio-caretechnology.com/nogall-biological-control-treatment/
3 Kerr and Bullard, 2020
4 USA Environmental Agency (EPA) Technical Document (006474) Agrobacterium radiobacter strain K1026
5 Company website: https://www.pivotbio.com/corn
6 Company website: https://www.bioconsortia.com/
7 CTNBio opinion 8833/2023
8 Miklau et al, 2024

9 CTNBio Opinion 7831/2021
10 Patent data https://patents.justia.com/patent/20230034438
11 Company website: https://www.crobio.com/technology
12 Dar et al, 1993; Lindow and Panopoulos, 1988
13 Kaur et al, 2025; Patel et al, 2025

Source: the authors

3.2. Animal Feed

GMMs are currently being used in closed systems to produce feed additives including enzymes (phytase, xylanase and β-glucanase), amino acids and vitamins, thereby increasing nutritional efficiency and digestibility. They can also increase microbiome functionality by improving animal gut health, immunity and reducing the reliance on prophylactic antibiotics in livestock. Some of these products can indirectly improve efficiency and sustainability by, for example, reducing phosphorus amounts in manure (Young and van Eenennaam, 2017).

Other applications include GMM-containing probiotics developed as feed additives by UK startup Folium Science, to modulate the microbiome of animals by removing harmful microbes, such as *Salmonella* and *Campylobacter*. The company aims to improve animal health and welfare, as well as reduce the need for antibiotics. Their product, BiomElix® One, specifically targets *Salmonella* and has been approved by Brazil's Ministry of Agriculture (MAPA) for use as an animal feed additive and included in their Positive List of Feed Ingredients. However, no release beyond feeding trials has been identified (Cogan et al, 2020).

Another European startup in this field is Sundew, based in Denmark. Sundew develops solutions for aquatic systems based on microalgae, for disease prevention and targeting invasive species. The company's first product is a microbial extract derived from a conventional microbe. In addition, the company is developing GM microalgae for future use as delivery systems for vaccines and silencing RNAi to prevent disease.

In addition to the examples described above, research is also ongoing to reduce grazing livestock's exposure to naturally occurring toxic compounds. A specific example is that of a gene edited endophyte that no longer produces the toxin ergot, which is naturally produced by native endophytes of tall fescue grass. When inoculating tall fescue with this strain, researchers from the University of Kentucky Foundation observed improved performance of grazing animals (Florea et al, 2021). This endophyte strain was reviewed by the US Animal and Plant Health Inspection Service (APHIS) and determined not to fall under their regulation. While there is currently no commercial product on the market, the research included field trials over several years.

Table 4. Examples of GMM-containing feed additives under development

Microorganism	Purpose	Developmental Stage
Escherichia coli	GM bacteria that modulates the animal microbiome by eliminating *Salmonella* while preserving beneficial microbes[1]	R&D in the UK Approved in Brazil for use as an animal feed additive and included in their Positive List of Feed Ingredients Folium Science
Escherichia coli	GM bacteria that modulates the animal microbiome by eliminating *Campylobacter* while preserving beneficial microbes[2]	R&D in the UK Folium Science
Fungal symbiont (endophyte) *Epichloë* spp.	GM endophyte that does not produce the compounds (ergot alkaloids) in tall fescue, that are toxic to grazing animals[3]	Research including field trials as forage in the US (2001-2003) University of Kentucky Foundation
Microalgae	GM microalgae for use as delivery systems for vaccines and silencing RNAi to prevent disease	R&D in Denmark Sundew

1 Company website Innovative feed ingredient harnessing CRISPR in its natural microbiome setting gains approval - Folium Science
2 Company website https://foliumscience.com/2024/07/09/folium-science-using-guided-biotics-to-reduce-campylobacter-in-farming-systems-for-sustainable-agriculture/
3 Florea et al, 2021
4 Company website https://www.sundew.bio/microalgae

Source: the authors

3.3. Biomining

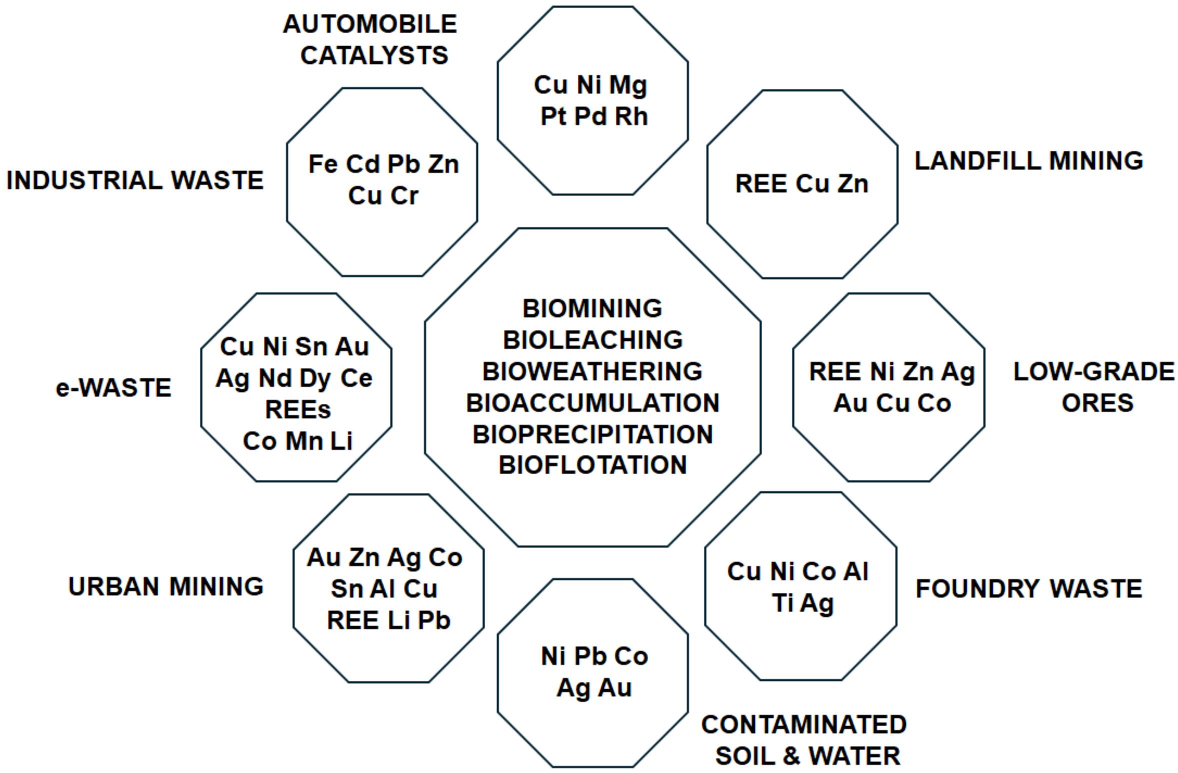
Biomining refers to the use of living organisms, primarily microorganisms to extract metals from ores and other solid materials. At present, there are no GMMs used in global commercial scale biomining operations, although this is an active area of R&D to enhance the efficiency, speed and environmental sustainability of metal recovery. For example, the use of sophisticated high-throughput genome editing and sequencing tools has allowed the production of organic acids by GMMs for the biomining of rare earth elements (REEs) (Schmitz et al, 2021). REEs are used in electronic, optical and magnetic devices (Vo et al, 2024) and are critical for capitalising on renewable energy, military equipment, electric vehicles and other products of advanced engineering. REEs are dispersed in the earth's crust at low concentrations and are subject to insecure supply chains owing to uneven geographical distribution, geopolitics and challenges in their purification at industrial scales. Currently, China controls ~70% of global REE mine output, as well as 85% of refining capacity and ~90% of magnet manufacturing[22,23].

22 Mining Technology (2025) China currently controls over 69% of global rare earth production
23 Horizon Magnet Technologies (2026) Top 10 China Magnet Manufacturers in 2026

Biomining approaches for the recovery of metals, particularly REEs, includes a plethora of technologies such as bioleaching, bioweathering, biosorption, bioaccumulation, bioprecipitation and bioflotation, depending on the specific mining scenario and stage of the recovery process (Figure 4).

Bioleaching is employed in two separate scenarios: urban waste streams containing critical metals, and natural ore processing at scale in geographical locations. Urban mines encompass recyclable components within end-of-life electronic products, obsolete infrastructure and industrial waste, combustion residues, ash and foundry waste, spent batteries, automobile catalysts and magnet scrap (Kumar et al, 2026). Conventional microorganisms have been used in ore bioleaching with some success, and GMMs are being developed to overcome the limitations of conventional strains, such as slow process times and sensitivity to fluctuating site conditions, including temperature, pH and metal concentrations (Somayaji et al, 2022). For example, the addition of poly-histidine tags to the cell surface of an acidophile microorganism, the overexpression of an enzyme and the manipulation of quorum sensing circuits, all improve metal solubilisation, particularly of copper (Cu) and cobalt (Co), in urban waste matrices. In addition, metabolic engineering to improve cyanide nutrients more than doubled the recovery of gold (Au) from electronic waste (Somayaji et al, 2022).

Figure 4. Applications of microorganisms for biomining



Source: the authors

Other REE extraction processes include bioweathering, which involves the erosion, decay and decomposition of minerals by microorganisms. This can be done on-site and is particularly applicable to iron (Fe), phosphorus (P) and silicon (Si), although less so to REEs. Laboratory-scale biosorption of REEs with microalgae has proven effective for neodymium (Nd), europium (Eu) and cerium (Ce), whilst macroalgae are effective with praseodymium (Pr) and thulium (Tm) (Vo et al, 2024). Another interesting approach exploits magnetic bacteria which can recover REEs such as lanthanum (La) from saline wastewater. GMMs can also be developed to overexpress REE-binding proteins to bind e.g., ytterbium (Yb), thulium (Tm), erbium (Er) and terbium (Tb). A related and complementary technology is bioaccumulation**,** which involves the accumulation of REEs inside microbes' cells (Vo et al, 2024). Bioaccumulation and biosorption both function well in the harsh environment of mining waste, but have yet to offer a cost-effective route to recover REEs commercially.

The formation of carbonates, phosphates and sulphides by microbial activity has been investigated for the bioprecipitation of REEs, either directly or indirectly, via oxidation, to create biogenic materials (silica, iron oxides, manganese oxide), which themselves bind and co-precipitate REEs (Wu et al, 2021). Bioprecipitation has been developed to pilot scale in some cases, but not as yet for REEs.

The final process applicable to REEs is bioflotation, where microorganisms either change the hydrophobicity of minerals by surface adsorption, microbial metabolism or forming extracellular polymeric products, to facilitate the adsorption of REEs and thus the recovery of minerals after bioflotation. This technology efficiently recovers metals such as Fe, Cu, lead (Pb) and zinc (Zn), but is still being considered for REE recovery. In all cases, the effects of pH, temperature, metal concentrations, aeration, nutrients and pulp density (mass mineral/unit volume) and on-site environment, influence recovery efficiency.

Bio-oxidation is particularly appropriate for Au recovery, with evidence of commercial success. Furthermore, the treatment of heavy metal-loaded waste streams with GMMs equipped for biotransformation, enzymatic processes, synthesis of metallothioneins and exopolysaccharides, is growing in popularity. Helical protein channels, secondary carriers and primary active transporters have all been engineered into appropriate host strains, able to bioaccumulate heavy metals such as mercury (Hg), As, nickel (Ni), Co, and Cu (Misra et al, 2024).

The biomining of Cu is relatively mature but needs to respond to increasing pressure created by electrification, data centres and the green energy transition. This has resulted in a "copper cliff" whereby, between now and 2050, the world is forecast to need more Cu than in the entire history of mankind. Ore grades have fallen from 3% a century ago, to 0.7% today and traditional extraction processes only recover 20-60% of available Cu from low grade ores (Garcia et al, 2025). By increasing recovery by up to 80%, compared to traditional methods, marginal deposits can be transformed by biomining with microorganisms that thrive in highly acidic environments and tolerate high temperatures, whilst being able to derive energy from inorganic substrates. Modern biomining incorporating AI optimisation and monitoring can now significantly increase Cu recovery rates by 10-80%. At present, improvements of >60%, are already achieved using conventional microbes. Methodologies developed for Cu biomining are equally applicable for lithium (Li) extraction, Ni recovery, Au liberation from refractory ores, uranium (U) solubilisation from low-grade deposits and REE recovery.

As described in this section, the use and tailoring of microbes for biomining shows huge potential, with several startups already starting to emerge. Three startups were specifically identified as developing GMMs for biomining: Endolith[24], is developing modified microbes to recover Cu and other critical minerals from ore. Results from simulated field conditions outperformed conventional

[24] Company website: https://www.endolithmining.com/

approaches to low-grade heap leaching and revealed new value in mineralised waste previously considered uneconomic to process[25]. The company reports advancing field deployment in North and South America; RareTerra's[26] modified microbes aim to selectively capture and separate REEs from ore, concentrates, e-waste and swarf, at ambient conditions; and REEgen[27] is developing GMMs to optimise recovery of REEs and other critical elements from industrial residues (steel slag, e-waste, spent catalysts and coal ash), recycled materials and ore. Despite this progress, there are currently no known GMMs approved for release by these companies or other organisations.

Table 5. Examples of GMMs being developed for biomining

Microorganism	Purpose	Developmental Stage
Microbes	GMMs tailored to recover Cu and other critical minerals from heap-leach operations[1]	R&D in US with deployments advancing with global miners in North and South America Endolith
Bacteria	GMMs developed to recover REEs from ores and unconventional feedstocks, including waste[2]	R&D in US REEgen
Microbes	GMMs programmed to selectively capture and separate lanthanides (REEs) from ore, concentrates, e-wastes and swarf[3]	R&D in US RareTerra

1 Company website: https://www.endolithmining.com/
2 Company website: https://www.reegen.tech/
3 Company website: https://rare-terra.com/

Source: the authors

3.4. Bioremediation Waste Treatment and Pollution Control

Land and water pollution arises when toxic contaminants seep or run off into the surrounding soil and groundwater and ultimately pollute fields and natural habitats, thereby damaging ecosystems, spawning diseases and ultimately contaminating food and drinking water. Bioremediation holds the promise of an eco-friendly and, potentially, cost-effective route for mitigation. The process involves the use of living organisms deployed at contaminated sites to degrade pollutants. In some cases, bioremediation is combined with the production of biomass and/or non-toxic materials (Chatterji et al, 2025). The use of GMMs in bioremediation enhances the innate functions of bacteria, fungi and algae to degrade specific pollutants such as oil, (cyclo)alkanes, (poly)aromatic hydrocarbons, plastics, heavy metals and persistent chemicals (Singh et al, 2011; Rafeeq et al, 2023). Using modern tools such as CRISPR, synthetic biology and metabolic pathway engineering, it is possible to enhance specific enzymes, create novel multi-gene pathways for extended degradation, or combine

[25] News - Mining Technology (2025) Endolith, BHP's TAD and Unearthed achieve copper extraction milestone

[26] Company website: https://rare-terra.com/

[27] Company website: https://www.reegen.tech/

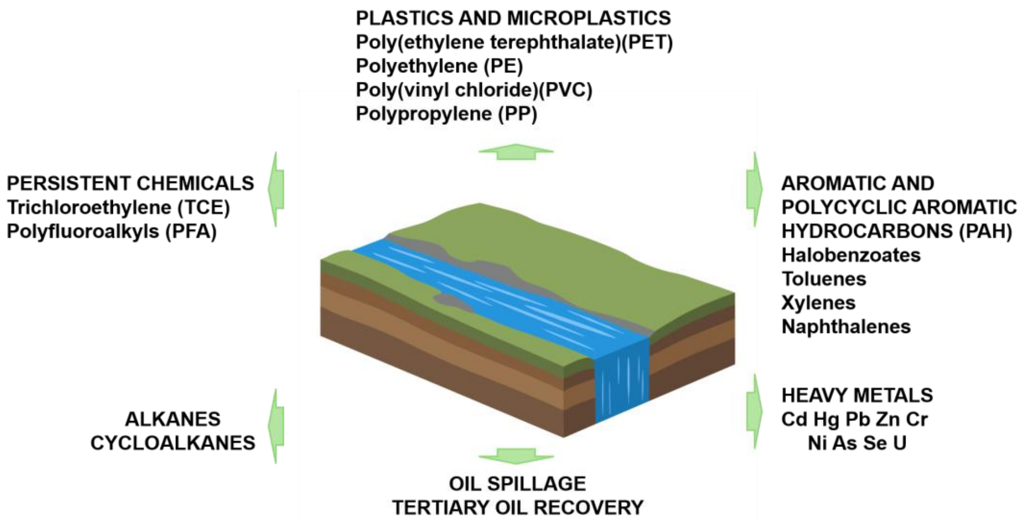
GMMs with GM plants to create multi-pronged bioremediation, thereby leading to faster, more targeted, and cost-effective cleanup of contaminated environments (Figure 5).

For example, mutations in a specific combination of enzymes enabled the degradation of various grades of crude oil (Wang et al, 2023). More recently, a microorganism, *Vibrio natriegens*, has been modified to degrade five different hydrocarbons, biphenyl, phenol, naphthalene, dibenzofuran and toluene in industrial wastewater, seawater and contaminated saline soil (Su et al, 2025).

Synthetic biology tools can also be used to develop microbial communities to create metabolic networks and facilitate their interaction to improve degradation rates. For example, modified *E. coli* was coupled with modified *Pseudomonas aeruginosa* to degrade the pollutant phenanthrene in a two-step process, allowing 71% degradation in nine days (Jia et al, 2019).

Other pollutants include commodity plastics. Plastic-degrading microbes include bacteria, fungi and microalgae, whose variety of enzyme-encoding genes have been engineered into host organisms, like *E. coli*, conferring the ability to degrade a number of plastics, including the very challenging poly(ethylene terephthalate) (PET) (Martin-Gonzalez et al, 2024).

Figure 5. Accumulation of pollutants in soil and water



Source: the authors

Bioremediation technology using GMMs has also been exploited for the cleansing of obstinate heavy metal pollutants (Singh et al, 2011). For example, a heavy metal-tolerant GMM has been developed expressing a metallothionein (protein with strong metal-binding capacity) from mouse on its cell surface. Inoculation of cadmium (Cd)-polluted soil with the GMMs significantly reduced the toxic effects of the metal on the growth of plants (Valis et al, 2000). Other GMMs exploiting various enzymatic processes have been developed to detoxify the effects of chromium (Cr), Hg, As, Cd and Ni.

A group of pollutants that have recently received a lot of attention, are per- and polyfluoroalkyl substances (PFAS). PFAS are widely used in consumer products, but are highly persistent in the environment and hence termed “forever chemicals”, owing to their lack of degradability in nature (Olawade et al, 2025). Most research on how to degrade these compounds is relatively recent, but several studies have already demonstrated that some microorganisms can partially degrade PFAS and other fluorinated compounds, although rates are slow and incomplete without genetic upgrading. This has led to modifying microbial strains which have the capacity to catalyse cleavage of halogen-carbon bonds (dehalogenases) or the ability to modify PFAS (oxygenases) under controlled conditions (Smorada et al, 2024).

A concrete example of the successful deployment of GMMs in bioremediation, concerns the emergency deliberate release of the modified, phenol-degrading, GM *Pseudomonas putida* PaW85, following the largest underground fire in an oil shale mine in the former USSR (now Estonia). The fire burned from November 1988 to February 1989 and resulted in thousands of tonnes of phenol-polluted water eventually flowing through rivers to Lake Peipus and to the Baltic Sea (Peters et al, 1998). The pollution with phenols exceeded 400 times the accepted limit (1-100mg/kg) in the mine and 5-6 times in the local rivers (Parakhonsky, 1995). The GMM was inoculated into the mine enclosure where it successfully reduced phenol levels over time (Chemla et al, 2025). Analyses of water samples from the mine and a nearby watershed six years post-release, identified a phenol-degrading gene cluster in four native bacterial species, but the released GM *P.putida* PaW85 could not be detected. In the absence of samples from before the release, the authors could not fully rule out the possibility that a similar cluster was previously present in nature.

In addition to the above example, some startups were identified as developing GMMs for providing services in water and waste treatments. For example Alan Environmental[28], whose products include modified bacteria for digesting fats, oils, and grease in wastewater systems; Aquasaic[29], developing a modified yeast designed to capture heavy metals, including Pb, As, and Hg, from various wastewater sources, with a specific focus on mining wastewater; and Lysosome Resources[30], developing a modified yeast designed to transform environmental pollutants, particularly PFAS on legacy sites, and material recovery, aiming to extract commercial value from complex waste streams. While they are all developing or using GMMs, it is unclear whether they are targeting closed systems, deliberate environmental release, or both.

The potential to utilise GMMs for bioremediation of soils and water will depend on their efficiency and speed relative to their natural counterparts, their cost-effectiveness compared to traditional physical or chemical treatments, and their ability to function under ambient conditions with reduced fire or explosion risks. To date, most of the cited research is laboratory-based with virtually no real-world deployment. One notable exception is the successful case of the bioremediation of the mine shaft in the former USSR, now Estonia (Peters et al, 1998).

[28] Company website: https://www.alanenv.com/

[29] Greentown Labs: https://greentownlabs.com/members/aquasaic/

[30] Company website: https://www.paliwoda.com/lysosome/

Table 6. Examples of GMMs developed or being developed for bioremediation, waste treatment and pollution control.

Microorganism	Purpose	Developmental Stage
Bacteria, Fungi	GMMs for the degradation of harmful chemicals, including PFAS[1]	R&D in US Lysosome Resources
Bacteria (*Pseudomonas putida* CR30RNSLL (pADPTel))	GMM developed to degrade atrazine herbicide in soil[2,3]	Research Field trials approved in Canada in 2001
Bacteria (*Pseudomonas putida* PaW85)	GMMs programmed to degrade phenol[4]	Emergency release in former USSR (now Estonia) in 1989 No commercialisation
Various bacteria and fungi (Pseudomonadales, Enterobacteriales, Sphingomonadales, Ascomycota)	GMMs developed for degrading a variety of target pollutants from soil or water, including hydrocarbons, (nitro)benzene, toluene, phenol, pesticides, heavy metals, nicotine, etc...[5]	Research with some including field trials

1 Company Website: https://www.paliwoda.com/lysosome/
2 Miklau et al, 2024
3 Canda New substances: risk assessment summary: 10642 - Research Trials using Pseudomonas putida CR30RNSLL(pADPTel)NSN 10642
4 Chemla et al, 2025; Peters et al, 1998
5 Sayler and Ripp, 2000; Gong et al, 2016; Verma et al, 2019; Fedeson et al, 2020; Zhou et al, 2020; Deng et al, 2022; Maleki and Shahpiri, 2022; Miklau et al, 2024.

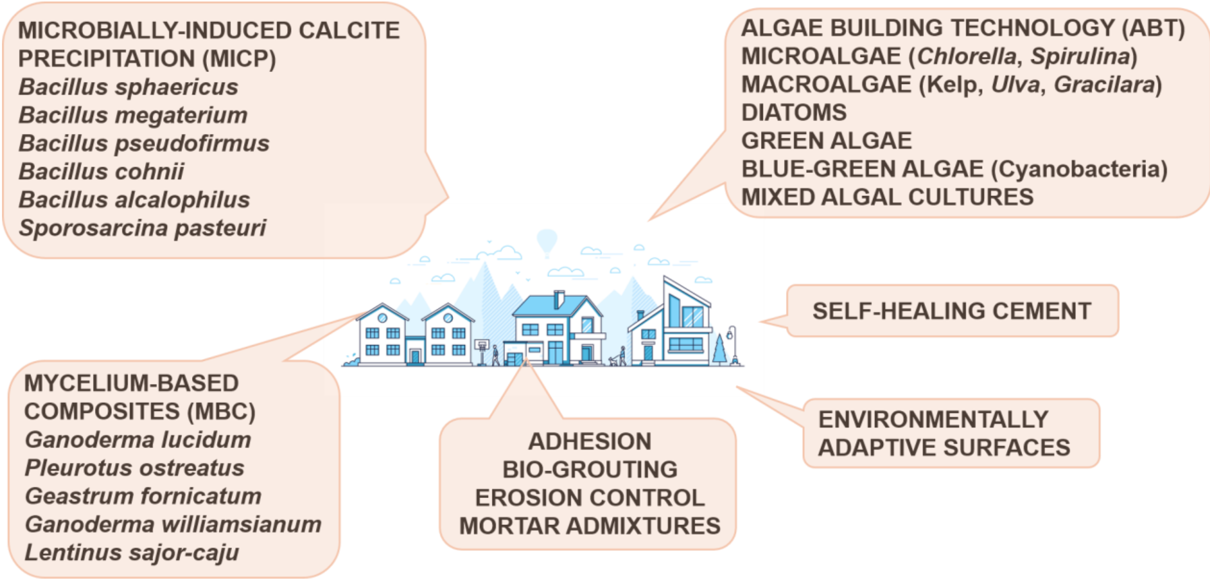
Source: the authors

3.5. Construction Materials

Biomaterials derived from renewable resources offer significant advantages in the construction industry over existing building materials, particularly in terms of greenhouse gas emissions, energy usage, reduction in waste and depletion of non-renewable resources (Chen et al, 2024)[31]. Not surprisingly, biomaterials have been proposed as a sustainable alternative to plastics and concrete in the construction and infrastructure sectors. “Living biomaterials” are a new class of sustainable biomaterials, that can be grown from living organisms or incorporate living cells, to furnish entirely unique capabilities, such as self-healing and carbon sequestration (Figure 6). For example, mycelium-based composites (MBC) from fungal roots, comprise highly dense filaments or hyphae, which comprise proteins, glucans and chitin and can be grown on solid wastes, such as wood sawdust, straw, hemp, wheat grains, coconut husk, rice hulls, wood chips and hay (Wen et al, 2025). Wood-decaying fungi, that degrade lignin, can be cultivated commercially on a global scale. MBCs can be fashioned within moulds to produce light, fire-resistant, thermal/acoustic insulation panels, bricks, packaging, furniture and automative materials, as a sustainable alternative to traditional insulation materials.

[31] United Nations Environment Programme (2024) Mainstreaming Sustainable Solutions to Cut Emissions from the Building Sector: Global status report for buildings and construction. ISBN: 978-92-807-4131-5.

Figure 6. Applications of microorganisms in the construction sector



Source: the authors

Microbially induced calcite precipitation (MICP) enables autonomous healing strategies for concrete, exploiting the metabolic ability of specific microorganisms to generate carbonate ions, to induce the precipitation of calcium carbonate from calcium within concrete pores or cracks (Šovljianski et al, 2024). The anionic bacterial cell wall serves as a nucleation site for the biological formation of a mineral filler that repairs the cracks.

In addition, bacteria can form biofilms, where structured microbial communities are embedded in a matrix of extracellular polymers. This biofilm acts as an adhesive and secures the bacteria within the cracks. Biofilms thus act as microenvironments for mineral precipitation and form protective coatings on e.g., exposed steel to mitigate corrosion, by restricting the ingress of O_2 and ions (Roudbari, 2025). Bacterial biopolymers, such as xanthan gum, enhance soil cohesion and water retention in eco-grouting, erosion control and mortar admixtures. Engineered biofilm coatings, comprising mussel foot proteins, are candidates for robust adhesion and corrosion resistance, where they are particularly vital in underwater or chloride-rich environments, where conventional sealants fail (Onyeaka and Ekwebelem, 2023).

Algal building technology exploits microalgae, macroalgae, diatoms, green algae, cyanobacteria (blue-green algae) and mixed algal cultures and allows architects to combine adaptive environmental compatibility with aesthetics (Roudbari, 2025). Cultivating algae in exterior panels or 3D printed constructs, provides adaptable colouring, shade, pollutant absorption and clean air, as well as control of natural daylight, reducing indoor temperature and glare. Algal-based materials are already being trialled in Hamburg (Bio-Intelligent Quotient House[32]), in algal foam[33], cement, 3D printed materials and algal biofilm faces. Nevertheless, despite the enthusiasm for these approaches, many challenges remain, including production and processing, weather resistance,

[32] Bio-Intelligent Quotient House: www.architonic.com

[33] Company website: www.jnbot.com

lifespan, energy efficiency, maintenance, scalability, public perception, biosafety and regulatory barriers.

The leading-edge of construction biotechnology leverages genetic circuits, synthetic promoters and quorum-sensing elements to modify bacteria to detect environmental cues, such as moisture, pH shifts or mechanical stress, and initiate selective responses, including carbonate precipitation, polymer secretion, or the release of healing compounds. These engineered living systems could lead to the development of adaptive, intelligent self-regulating infrastructure, capable of sensing environmental changes via real-time degradation monitors and stress-responsive joint sealants. In combination with AI modelling tools, these bacterial systems can create the basis for future smart integrated infrastructure for the built environment.

While there is currently a lot of activity leveraging conventional microorganisms for the construction sector, no information could be found regarding the development or use of GMMs for this purpose.

3.6. Cosmetics and Personal Care

Recent advances in GMMs in the cosmetics and personal care sector are addressing sustainability and personalised approaches by pivoting away from traditional plant and animal sources for high-value ingredients (Atallah et al, 2025). One trend is the increasing interest in so-called "postbiotics", i.e. metabolic byproducts created by inactivated GMMs and functional ferments to improve skin barrier function and moisturisation and reduce inflammation (Lim et al, 2026). In many of these cases, CRISPR is being used to optimise metabolic pathways, such as to enhance hyaluronic acid production by up to 86% in cyanobacteria or for producing natural pigments (Erat and Addor, 2025). GMMs have also been developed for the treatment of acne, anti-ageing and UV protection.

Of note, GM skin bacteria, particularly *Cutibacterium acnes*, are emerging as "living therapeutics" for skin disorders by delivering targeted anti-microbial peptides to hair follicles to treat conditions such as acne, eczema, and skin ageing, without disrupting the overall skin microbiome (Knödlseder et al, 2024). This approach is currently being developed by Barcelona-based spin-off Synflora[34], and funded by two European Innovation Council (EIC) grants[35]. Similarly, postbiotics derived from *Lactobacillus*, *Bifidobacterium*, *Bacillus*, and commensal *Staphylococcus* species reduce inflammation and facilitate restoration of the skin barrier (Lim et al, 2026).

Another example involves oral hygiene: dental cavities occur when the native bacteria present in the human mouth, *Streptococcus mutans,* forms biofilms and demineralises tooth enamel in acidic conditions. A potential remedy recently approved for environmental release and commercialised in the US by Lumina Probiotics[36], is a GM strain of *Streptococcus mutans* deficient in the enzyme lactate dehydrogenase. When taken as a probiotic, the company claims it outcompetes the oral microbiome to eliminate the bacteria that release lactic acid after meals, thereby protecting the enamel and reducing bad breath (Mulla et al, 2025)[37]. The product was originally developed by Lantern Bioworks, who applied for approval in the early 2000s as an oral therapeutic with the US

[34] Company website: https://synflora.com/

[35] SKINDEV Pathfinder grant (2023-2027) and SkinEngineering EIC Transition grant (2025-2028)

[36] Company website: https://luminaprobiotic.com/

[37] Scientific American (2024) This Start-Up Wants You to Put Custom Bacteria on Your Teeth

Food and Drug Agency (FDA), but faced several hurdles. It was later released as cosmetic in 2023 by Lumina Probiotic.

Table 7. Examples of GMMs developed for use in cosmetics and personal care products

Microorganism	Purpose	Developmental Stage
Bacteria (*Streptococcus Mutans,* BCS3-L1)	Prevention of cavities by inhibiting acidogenic bacterial conversion to lactic acid[1,2]	Commercialised in 2023 in the USA Lumina Probiotics
Cutibacterium acnes, Staphylococcus aureus	Treatments for skin disorders such as acne, eczema and ageing via anti-microbial peptides[3]	R&D, Conducted Preclinical trials Benefiting from EIC Pathfinder and Transition Grants Synflora

1 Company website: https://luminaprobiotic.com/
2 Scientific American (2024) This Start-Up Wants You to Put Custom Bacteria on Your Teeth
3 Company website: https://synflora.com/skinengineering/

Source: the authors

3.7. Defence

Synthetic biology is creating new paradigms for biodefence, national security, medical countermeasures and advanced materials. Key developments include AI-driven design and "programmable" biology, which has revolutionised the design and automated production of synthetic variants of novel proteins with bespoke functions, the creation of minimal host organisms with modified or entirely synthetic genomes, and AI-designed viruses using models trained on viral genome databases. Such implications have prompted the development of DNA-based biosecurity screening and pathogen-agnostic[38] defence technologies[39].

Specific defence applications of GMMs include the detection of emissions from submarines or explosives in landmines (Belkin et al, 2017), as well as advanced protective and responsive garments and self-healing for camouflage, construction, ships and aircraft. Most of these applications will be for environmental release. However, due to the sensitive nature of this sector, little to no publicly available data could be found.

[38] Pathogen-agnostic refers to diagnostic or detection methods that can identify any pathogen without prior knowledge of its specific type or species

[39] Johns Hopkins (2025) APL Technical Digest, Volume 37, Number 4, Article 2400429-7

Table 8. An example of GMMs for potential applications in defence

Microorganism	Purpose	Developmental Stage
Bacteria (*Escherichia coli*)	GMM biosensor strain capable of detecting TNT- and DNT-related explosives for the remote detection of anti-personnel mines[1]	R&D with field trial in 2017 in Israel

1 Belkin et al, 2017 ; Chemla et al, 2025

Source : the authors

3.8. Food and Beverages

Food production and quality are already benefiting from GMMs and modern tools of precision fermentation, synthetic biology, genome editing and artificial intelligence in closed systems (Mirsalami and Mirsalami, 2025). In addition, probiotics, food supplements containing live GMMs aimed at conferring health benefits when ingested, are already commercially available. Both conventional and GM probiotics often leverage lactic acid bacteria (LAB) from the genera *Lactobacillus*, *Lactococcus*, and *Bifidobacterium* as their host strain. LAB are considered particularly appropriate host organisms that can be genetically modified for therapeutic and industrial applications (Mugwanda et al, 2023). The principal advantage of GM probiotics is that they may confer functions not natively expressed by endogenous microbes. One example is the recombinant oral *Lactococcus lactis* probiotic expressing human alcohol dehydrogenase, that has been shown to attenuate damage caused by acute alcohol consumption in mice (Jiang et al, 2023). Whilst the human alcohol dehydrogenase probiotic is still experimental, other commercial products use different methods. The US startup ZBiotics commercialised a consumer hangover preventative probiotic that uses a modified *Bacillus subtilis* to express an enzyme that degrades acetaldehyde, the toxic byproduct of alcohol that is the primary cause of the usual symptoms of headaches and nausea (Nosova et al, 1996). While there is little publicly available data demonstrating its efficacy to reduce hangovers, apart from a small toxicity study in rats (Naidu et al, 2019), ZBiotics has doubled its sales of the probiotic every year since its launch in 2019, and reached company-wide profitability in 2023. It has since launched its second GMM probiotic in 2023, which converts sugar into fibre in the human gut, thereby addressing health challenges linked to unhealthy diets and high sugar intake.

As consumer-targeted products, successful companies tend to focus their GMM-containing probiotics towards improving consumer health and wellbeing. This is further exemplified by another US startup called Bactose[40], addressing lactose intolerance. Its GMM-containing probiotic food supplement, commercialised in 2025, is made up of modified *Lactobacillus acidophilus* bacteria that colonise the human intestine and actively secrete lactase enzymes.

A final example involves the US startup Florey Bioscience, which is developing a probiotic containing a modified yeast aimed as a medical food for the dietary management of antibiotic perturbations

[40] Company website: https://bactose.com/pages/about-us

of the gut microbiome[41]. In addition to improving the wellbeing of patients, the probiotic also aims to reduce the growth of harmful, antibiotic-resistant pathogens in the gut during treatment.

Table 9. Examples of GMM-containing probiotic food supplements

Microorganism	Purpose	Developmental Stage
Bacillus subtilis ZB183™	GM probiotic bacterium that digests acetaldehyde, the byproduct of drinking alcohol, responsible for hangovers[1]	Commercialised in 2019 in the US ZBiotics
Bacillus subtilis ZB423™	GM probiotic bacterium that converts sugars in the gut into fibre[2]	Commercialised in 2023 in the US ZBiotics
Lactobacterium /Bifidobacterium spp	GM probiotic bacteria producing lactase in the gut, enabling lactose intolerant people to consume dairy products[3]	Commercialised in 2025 in the US Bactose
Yeast FLR-101	GM probiotic yeast for the dietary management of antibiotic perturbations of the gut microbiome[4]	R&D in the US Florey Biosciences

1 Company website https://zbiotics.com/pages/how-it-works
2 Company website https://zbiotics.com/pages/how-sugar-to-fiber-works
3 Company website https://bactose.com/pages/about-us
4 Company website https://florey-biosciences-developer.squarespace.com/

Source: the authors

3.9. Textiles and Biogarments

Applications of GMMs in the textile and biogarmentry industries already exist in closed systems. For example, bacterial and fungal celluloses are being leveraged as alternative biomaterials for the textile industry (Fernandes et al, 2025), while yeast have been reprogrammed to produce a protein identical to bovine collagen, for animal-free leather[42]. More recently, the bacterium *Komagataeibacter rhaeticus* has been modified to express tyrosinase to create a strain that grows self-pigmenting cellulose (Walker et al, 2025). Such solutions often provide more sustainable alternatives and allow lower production costs, reduced carbon footprint and shorter cultivation times (Yang et al, 2024; Liu et al, 2025).

Biogarmentry, the creation of living textiles, also known as engineered living materials (ELMs), is shifting the fashion industry paradigm from “buy-use-dispose” to “buy-care-compost” with key developments including air-purifying clothing, algal-based textiles that require no washing, 3D-printed materials that can photosynthesise and self-repair, and the introduction of microbial weaving technologies that use bacteria to grow materials that are strong, lightweight and act as a

[41] Company website https://florey-biosciences-developer.squarespace.com/
[42] The Economist (2017) Leather grown using biotechnology is about to hit the catwalk

hybrid alternative to spun or woven textiles[43]. The most prominent development involves fabrics that are "alive" utilising single-cell green algae (*Chlamydomonas reinhardtii*) spun with nanopolymers to turn carbon dioxide into oxygen. These clothes change colour and pattern as the algae grow and do not require traditional washing, just misting with water periodically to maintain the living organism. Further innovations include "end-of-lifecycle" technologies that incorporate biodegradability, such as laboratory grown T-shirts.

There is currently a growing trend to leverage conventional microbes for textiles and biogarmentry, with the use of GMMs still limited to closed systems.

[43] The Ethicalist - Sims J (2023) The Future of Fashion is Here: Biogarments that are ALIVE.

4. Startup and Scaleup Ecosystem

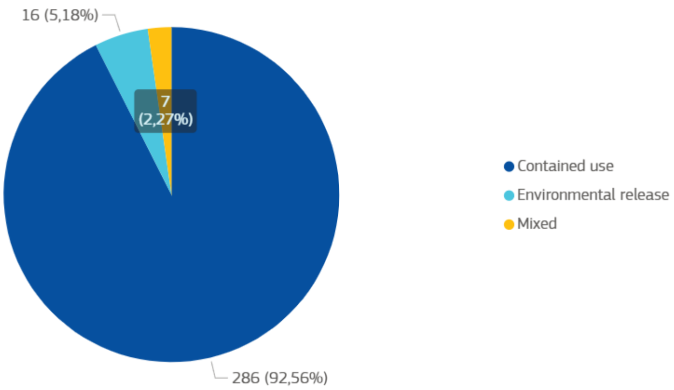
Startups and scaleups are a key driver for breakthrough innovation and creativity. As described in the EU Startup and Scaleup Strategy, published in 2025[44]: "*They excel in providing innovative solutions to client challenges, targeting niche or emerging markets and addressing problems often overlooked by larger companies. They are engines of disruptive innovation and create new markets…*". In line with this, most of the GMM-containing products identified in this report and which have recently received approval for release or placing on the market, were developed by startups or scaleups. This includes ZBiotics' GM probiotics to treat hangovers and increase fibre in the gut, Pivot Bio's GM Nitrogen-fixing biofertilisers and Lumina Probiotic's GM cavity-prevention product.

In order to gain an overview of the startups and scaleups landscape for developing and/or using GMMs, innovative firms in the sector were identified via Pitchbook[45], a proprietary venture capital database on startups and scaleups worldwide. In this section, we will briefly describe the innovation landscape, focussing particularly on applications targeting environmental release.

The authors identified 309 active startups and scaleups that were developing and/or using GMMs, or providing services related to the development of GMMs, excluding the human health and pharmaceuticals sector. The GMM relevance of each of these companies was checked by the authors. The cut-off date of the research was 30th November 2025.

Out of the 309 global startups and scaleups identified, 92.6% (286) were developing and/or using GMMs in closed systems, while the remaining were targeting environmental release (16 startups/scaleups) or developing/using GMM products that could be relevant for both, or for which it was unclear, based on the information available (7 startups/scaleups) (Figure 7).

Figure 7. Distribution of startups and scaleups developing or using GMMs for contained use, environmental release or both (Mixed). If it was unclear, they were categorised as Mixed. Sample population 309.



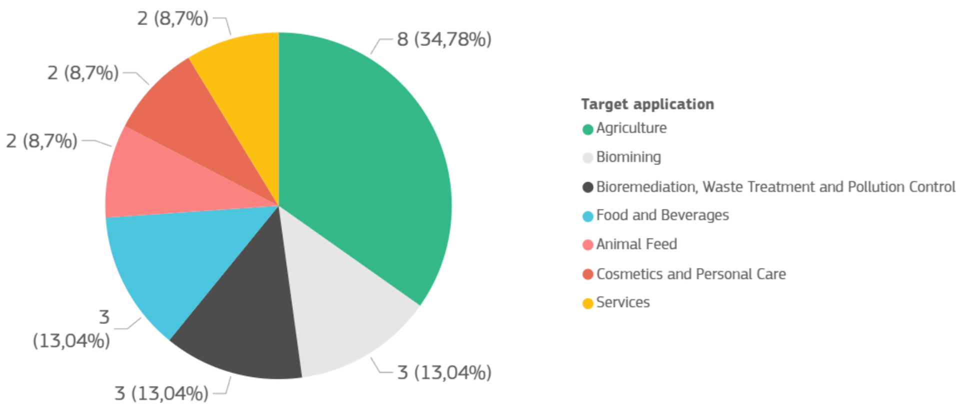
Source: the authors

44 European Commission (2025) - Communication to the European Parliament, the Council and the European Economic and Social Committee and the Committee of the Regions - The EU Startup and Scaleup Strategy - Choose Europe to start and scale

45 Website: https://pitchbook.com/

As can be seen in Figure 8, the 23 startups/scaleups developing and/or using GMMs specifically for environmental release, or potentially for both release and contained use, cover seven application areas. The main area is agriculture, with 8 startups operating in this field (34.8%). This is followed by biomining (3, 13%); bioremediation, waste treatment and pollution control (3, 13%); food and beverages (3, 13%); animal feed (2, 8.7%), cosmetics and personal care (2, 8.7%) and services (2, 8.7%).

Figure 8. Distribution of startups and scaleups developing or using GMMs specifically for environmental release or potentially for both environmental release and contained use, across application sectors. Sample population 23 firms.



Source: the authors

The full list of the firms is provided in Table 10, and in the following section, an overview of the different companies, as well as their products, if any, is provided[46].

Table 10. List of startups and scaleups developing and/or using GMMs for environmental release or potential for both environmental release and contained use.

Company Name	***Country***	***Target application***	***Employees***	***Age***	***Type***
BioConsortia	*United States*	*Agriculture*	*50*	*12*	*Scaleup*
Certis USA	*United States*	*Agriculture*	*145*	*30*	*SME*
CroBio	*United Kingdom*	*Agriculture*	*5*	*7*	*Startup*
Joyn Bio	*United States*	*Agriculture*	*90*	*9*	*Scaleup*
Pivot Bio	*United States*	*Agriculture*	*371*	*16*	*SME*

46 The following descriptions are based on information provided by companies' websites, Pitchbook, press releases, news and other online material. They serve to provide an overview of the companies' target market, as well as products they might have on the market or close to market.

Promip (Service division)	*Brazil*	*Agriculture*	*60*	*NA*	*Scaleup or SME*
ProspectaBio	*Brazil*	*Agriculture*	*8*	*5*	*Startup*
Switch Bioworks	*United States*	*Agriculture*	*29*	*4*	*Startup*
Folium Science	*United Kingdom*	*Animal Feed*	*19*	*10*	*Startup*
Sundew	*Denmark*	*Animal Feed*	*12*	*8*	*Startup*
Endolith	*United States*	*Biomining*	*26*	*3*	*Startup*
RareTerra	*United States*	*Biomining*	*NA*	*3*	*Startup*
REEgen	*United States*	*Biomining*	*9*	*4*	*Startup*
Alan Environmental	*United States*	*Bioremediation, Waste Treatment and Pollution Control*	*NA*	*NA*	*NA*
Aquasaic	*United States*	*Bioremediation, Waste Treatment and Pollution Control*	*NA*	*3*	*Startup*
Lysosome Resources	*United States*	*Bioremediation, Waste Treatment and Pollution Control*	*NA*	*3*	*Startup*
Lumina Probiotics	*United States*	*Cosmetics and Personal Care*	*NA*	*NA*	*NA*
Synflora	*Spain*	*Cosmetics and Personal Care*	*NA*	*NA*	*Startup*
Bactose	*United States*	*Food and Beverages*	*2*	*6*	*Startup*
Florey Biosciences	*United States*	*Food and Beverages*	*3*	*2*	*Startup*
ZBiotics	*United States*	*Food and Beverages*	*48*	*10*	*Startup or Scaleup*
AmpliOmics	*Brazil*	*Services*	*NA*	*1*	*Startup*
Gaia	*Israel*	*Services*	*7*	*5*	*Startup*

Source: data gathered by authors from Pitchbook (as of November 2025). Note that Lumina Probiotics is not listed in Pitchbook and was added manually, following the identification of its GMM product.

4.1. Agriculture

Eight companies were found in the area of agriculture, of which six from the US, two from Brazil and one from the UK. The company ages range from 2 to 30 years and the number of employees from 5 to 371.

Bioconsortia[47] – US-based developer of microbial solutions such as biofertilisers, biopesticides and biostimulants. Currently no GMM products are on the market, but one GMM biofertiliser was approved for field trials in Brazil[48]. Some work on GMMs in R&D, but active field trials and commercialisation restricted to conventional microorganisms.

Certis USA[49] – US-based manufacturer of biopesticides. Over 30 conventional biopesticides commercialised and at least one GM insecticide: Crymax® "*a genetically engineered strain of Bt containing toxins from both Bt kurstaki and Bt aizawai strains*"[50].

CroBio[51] – UK developer of GM root-associated microbes excreting materials that retain water in the soil, reducing irrigation needs and increasing drought resilience. Claims that the product also increases carbon sequestration in the soil and improves soil fertility. No known product commercialised yet.

Joyn Bio[52] – US-based developer of GMMs offering agricultural solutions e.g., N-fixation, pest control, disease management. Joint venture between Ginkgo Bioworks and Leaps by Bayer. No known products commercialised.

Pivot Bio[53] – US-based developer of GM N-fixing microbes. Products of the PROVEN® series were commercialised for maize since 2019 in the US and demonstrated to reduce the need for N-input (Burren et al, 2026). Currently developing products with these GM N-fixing microbes, adapted for cotton, wheat and sorghum.

Promip[54] – Brazilian developer of conventional biopesticides. The development of GMMs is mentioned on website, but no commercial products were found.

ProspectaBio[55] – Brazilian developer of conventional and GM microbial solutions, covering plant activators, biostimulants, biofertilisers, plant stress protectors, resistance inducers, insecticidal toxins, biopesticides and elicitors. Currently no known products commercialised.

Switch Bioworks[56] – US-based developer of GM N-fixing microbes. Currently no known products commercialised.

4.2. Animal feed

The two companies developing GMMs for feed additives are mature European startups, 8 and 10 years old, respectively.

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47 Company website: https://www.bioconsortia.com/

48 CTNBio opinion 8833/2023

49 Company website: https://www.certisbio.com/

50 Company website: https://www.certisbio.com/products/bt-biolarvicides/crymax

51 Company website: https://www.crobio.com/technology

52 Company website: https://leaps.bayer.com/companies/agriculture/joyn-bio

53 Company website: https://www.pivotbio.com/

54 Company website: https://promip.agr.br/

55 Company website: https://www.prospectabio.com.br/

56 Company website: https://www.switchbioworks.com/

Sundew[57] – Danish developer of solutions for aquatic systems based on microalgae, targeting disease prevention and invasive species. First product is a microbial extract derived from a conventional microbe. Company is currently developing GM microalgae for future use as delivery systems for vaccines and silencing RNAi to prevent disease.

Folium Science[58] - UK developer of GMM probiotics, used as feed additives, that modulate the microbiome of animals by removing harmful microbes, such as *Salmonella* and *Campylobacter*. BiomElix® One specifically targets *Salmonella* and has been approved by Brazil's Ministry of Agriculture (MAPA) for use as an animal feed additive and included in their Positive List of Feed Ingredients. No release beyond feeding trials has been found.

4.3. Biomining

All three companies identified in this sector are 3–4-year-old startups and headquartered in the US. On their respective websites, the desire to promote more sustainable mining, as well as the need to reduce dependency on imported critical minerals to ensure energy security, are mentioned as their key drivers.

Endolith[59] – US-based developer of modified microbes to recover Cu and other critical minerals from ore. Tailored microbes were successfully integrated into existing heap-leach operations, valorising mining waste and increasing recovery rates. Currently advancing deployment in North and South America.

RareTerra[60] – US-based developer of modified microbes that selectively capture and separate REEs from ore, concentrates, e-waste and swarf, at ambient conditions. No known activities involving release.

REEgen[61] – US-based developer of modified microbes to optimise recovery of REEs and other critical elements from industrial residues (steel slag, e-waste, spent catalysts and coal ash), recycled materials and ore. No known activities involving release.

4.4. Bioremediation, waste treatment and pollution control

All three companies identified seem to be startups, although limited information on company age and number of employees is available. In addition, all three companies are based in the US.

Alan Environmental[62] – US-based company offering water and waste treatment products and services to private and public waste management and environmental services companies. Products include modified bacteria for digesting fats, oils, and grease in wastewater systems. Not clear if activities restricted to contained use or also relevant for release.

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57 Company website: https://www.sundew.bio/
58 Company website: https://foliumscience.com/
59 Company website: https://www.endolithmining.com/
60 Company website: https://rare-terra.com/
61 Company website: https://www.reegen.tech/
62 Company website: https://www.alanenv.com/

Aquasaic[63] – US-based developer of a modified yeast designed to capture heavy metals, including Pb, As, and Hg, from various wastewater sources, with a specific focus on mining wastewater. No known activities involving release.

Lysosome Resources[64] – US-based developer of modified yeast designed to transform environmental pollutants from contaminated sites into valuable, upcycled materials. Activities include bioremediation, with a focus on "forever chemicals" (PFAS) on legacy sites, and material recovery, to extract commercial value from complex waste streams.

4.5. Cosmetics and Personal Care

Two firms, one based in the US and the other in Spain, were identified to be developing GMMs for this sector.

Lumina Probiotics[65] – US developer of an oral cosmetic probiotic containing a modified bacterium that aims to prevent cavities. GM strain (BCS3-L1) outcompetes oral microbiome to eliminate the bacteria releasing lactic acid after meals, protecting the enamel and reducing bad breath. Product originally developed by Lantern Bioworks as an oral therapeutic. Encountered hurdles related to approval as a medicinal product with the US FDA in the early 2000s, before being released as a cosmetic in 2023 by Lumina Probiotics.

Synflora[66] – research project in the process of being established as Spanish biotech startup. Synflora platform developing two lines of innovation: SKINDEV and SkinEngineering, both of which are receiving grants from the European Innovation Council. Projects address atopic dermatitis and acne, with clinical trials ongoing for the latter. No products commercialised.

4.6. Food and Beverages

All three companies in this field are US startups, with ZBiotics close to scaleup stage.

Bactose[67] - US-based developer of a GMM-containing probiotic food supplement intended to help people with lactose-intolerance digest lactose. Probiotic made of modified *Lactobacillus acidophilus* bacteria that colonise the human intestine and secrete lactase enzymes. GMM probiotic commercialised in 2025.

Florey Biosciences[68] - US-based developer of a probiotic (FLR-101) containing a modified yeast and developed as a medical food for the dietary management of antibiotic perturbations of the gut microbiome. Aims to improve patient wellbeing and reduce the growth of antibiotic-resistant pathogens in the gut during treatment. GMM probiotic not commercialised yet.

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63 Greentown Labs: https://greentownlabs.com/members/aquasaic/

64 Company website: https://www.paliwoda.com/lysosome/

65 Company website: https://luminaprobiotic.com/

66 Company website: https://synflora.com/

67 Company website: https://bactose.com/pages/about-us

68 Company website https://florey-biosciences-developer.squarespace.com/

ZBiotics[69] - US-based developer of GMM-containing probiotics. ZBiotics® Pre-Alcohol probiotic commercialised in 2019 and contains GMM that breaks down acetaldehyde, the byproduct of alcohol responsible for hangovers. ZBiotics® Sugar-to-Fiber, commercialised in 2023, contains GMM that converts sugar into fibre in the gut, addressing health challenges linked to unhealthy diets and high sugar intake.

4.7. Services

The two companies providing services business to business (B2B) are startups, with one based in Brazil and the other in Israel.

AmpliOmics[70] – Brazilian provider of B2B services, including the development of tailored GMMs, for the agro-industrial and environmental sectors. Likely involves environmental release of GMMs.

Gaia[71] - Israeli provider of B2B environmental services through development of custom GMMs, optimisation of their production and scale up for industrial use. Projects include plastic decomposition, bioremediation (oil spills and heavy metal pollution) and biomining. All involve environmental release of GMMs.

[69] Company website: https://zbiotics.com/

[70] Company website: https://ampliomics.com.br/en

[71] Company website: https://www.gaiabiotechnologies.com/

5. Conclusions

Microbes already play an essential role in key industrial sectors. As part of the green transition, additional sectors are looking to microorganisms to provide more sustainable solutions to current challenges and practices. Considering the limitations of conventional microorganisms, it is likely that GMMs will play an important role in tipping the scale towards more commercially viable alternatives. An early trend is already visible, with a considerable number of commercial GMM-containing products for environmental release having been launched in the last years. It is therefore expected we will witness GMMs transition from closed systems and niche applications to large-scale environmental deployment over the next decade. This is further supported by the speed of technological advancements, particularly gene editing technologies, in combination with automation, AI and ML.

The agricultural sector appears as the main target for GMM-derived innovations with the reduction of synthetic inputs and resilience to environmental stress the main objective. The development of GMMs for sectors such as bioremediation and biomining, offers novel solutions to address major environmental challenges, where conventional microbes have often failed to provide cost-efficient results. The high proportion of young startups working in this area suggests that this is an emerging field that will increase in the coming years, with currently the US leading the way.

Methods

Overview of the technological landscape and GMM applications

An overview of the landscape for GMMs and their applications was gathered between November 2025 and March 2026. This involved screening academic and grey literature, news articles, blogs and company websites, combined information from Pitchbook and insights from the authors.

Overview of the startups and scaleups landscape

For the identification of GMM-related startups, data from Pitchbook as of November 2025 was used. Pitchbook is a proprietary database containing venture capital data on startups. Pitchbook was interrogated using the following relevant keywords:

Precision fermentation or OR ((Microorganism OR Microb* OR Fung* OR Mushroom* OR Mycorrhizae OR Yeast* OR Bacteri* OR phage* OR cyanobacteri* OR microalgae OR biological OR biologicals) AND (Genetic modification OR Genetic engineering OR Engineered OR Genetically modified OR Editing OR Edited OR Synthetic biology OR CRISPR* OR GMM OR GM OR GMO))*

In total, 2,782 companies were identified from this search. A sample of 250 companies was used to fine tune the keywords and to develop a Large Language Model (LLM) prompt to guide GPT-4o classification, running on GPT@JRC. The LLM was tasked to determine whether each company was relevant for GMMs, meaning if it was developing and/or using GMMs. The following prompt was used:

Through a company description, you are going to perform an analysis of companies' involvement with Genetically Modified Microorganisms (GMMs) in a two-step approach:

Step 1: Determine whether the company operates solely in the medical, health, or pharmaceutical fields with business restricted to activities such as developing antibodies, drugs, therapeutics, medicines, or clinical research related to preventing or treating diseases, cancer, or human health. If the company's activities are exclusively in these areas, set Is_GMMs_relevant to HEALTH and omit further analysis. Specifically exclude companies that do not mention any involvement with genetically modified microorganisms or related technologies beyond human health applications.

Step 2: For companies not excluded in Step 1, determine whether the company is involved in the development or use of genetically modified microorganisms (GMMs) based on its business activities, products, and services. Consider the following guidelines:

Direct Involvement with GMMs: Does the company explicitly mention modifying, customizing, or engineering microorganisms (e.g., bacteria, yeast, fungi, microbes, microalgae) or their genetic material? Does the company explicitly mention precision fermentation or industrial biotechnology? Is the company using engineered, customized, or modified microorganisms (e.g., bacteria, yeast, fungi, microbes, microalgae) as production platforms to produce proteins, enzymes, biologicals, or other biomolecules?

Indirect Involvement: Does the company develop products (e.g., biologicals, enzymes, proteins) that are typically produced using genetically modified microorganisms? Does the company rely on recombinant protein expression, which often involves GMMs?

Service Providers and No Involvement: Are the company's activities restricted to providing services, technologies, platforms, equipment, reagents, or other materials for their customers to develop GMMs, proteins, or enzymes? Does the company specifically mention cell-free production without direct engagement in GMM-related processes? If the company strictly offers support services without developing GMMs themselves, set Is_GMMs_relevant to "false."

Examples of GMM Use: The company develops molecules or other products requiring scalable protein or enzyme production, which is often achieved through genetically modified microorganisms. The company may not explicitly state GMM involvement but describes activities (like protein engineering, tailored enzymes) that imply the use of GMMs in production processes.

Decision Criteria: Set Is_GMMs_relevant to "true" if the company is involved in GMM-based processes (either directly or indirectly). Set Is_GMMs_relevant to "false" if there is no involvement with GMMs. Set Is_GMMs_relevant to "unclear" if the information provided is not sufficient to confirm the direct or indirect involvement with GMMs.

If the company description is not provided, use your knowledge about this company and reflect this fact clearly in your reasoning part.

This resulted in 732 companies being considered relevant by the LLM. These 732 companies were then manually confirmed as developing and/or using GMMs or not. For this, the description provided by Pitchbook was checked, as well as the company website, where available. If the amount of data was insufficient to confirm relevance, the company was discarded. Companies that were out of business as of November 2025, were also excluded from the final list.

In the end, 309 companies were confirmed as developing and/or using GMMs. In addition to confirming the “GMM relevance” of each company, its target application area was determined, in addition to whether their activities linked to GMMs likely involved only in contained use, only in environmental release or possibly both.

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List of abbreviations and definitions

Abbreviations	Definitions
AI	Artificial Intelligence
APHIS	Plant Health Inspection Service
As	Arsenic
Au	Gold
B2B	Business to Business
Bt	Bacillus thuringiensis
Cas	CRISPR-associated nuclease
Cd	Cadmium
Cloud-based labs	Cloud-based labs use cloud computing technology to create virtual laboratory environments where users can e.g., perform experiments, training, and simulations, without the need for physical lab space
CRISPR	Clustered Regularly Interspaced Short Palindromic Repeats
CTNBio	Brazil's National Technical Biosafety Commission
Cu	Copper
DBTL	Design-Build-Test-Learn
E. coli	Escherichia coli
EIC	European Innovation Council
EPA	Environmental Protection Agency
EU	European Union
FDA	Food and Drug Agency
Fe	Iron

Abbreviations	Definitions
GM	Genetically Modified
GMM	Genetically Modified Microorganism
GMO	Genetically Modified Organism
gRNA	guide RNA
Hg	Mercury
La	Lanthanum
LLM	Large Language Model
MAPA	Brazil’s Ministry of Agriculture
MBC	Mycelium-Based Composites
MICP	Microbially Induced Calcite Precipitation
ML	Machine Learning
N	Nitrogen
NBTs	New Breeding Techniques
NGTs	New Genomic Techniques
Ni	Nickel
P	Phosphorus
Pb	Lead
PET	Polyethylene Terephthalate
PFAS	Per- and Polyfluoroalkyl Substances
R&D	Research and Development
REE	Rare Earth Element
SDG	Sustainable Development Goal

Abbreviations	Definitions
UK	United Kingdom
US	United States of America
USSR	Union of Soviet Socialist Republics
Wet Lab	A wet lab is a type of laboratory in which a wide range of experiments are performed, for example, characterising of enzymes in biology, titration in chemistry, diffraction of light in physics, etc.

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