



Co-funded by
the European Union



Novel Biotechnological Solutions in Climate Change Mitigation

2024-1-EL01-KA220-HED-000251373

Biotech Student's Guide to Future Projections



STUDENT'S GUIDEBOOK

EDITORS

Ioannis Kourkoutas, Democritus University of Thrace, Greece

AUTHORS

Maria Grigoriou, Democritus University of Thrace, Greece
George Skavdis, Democritus University of Thrace, Greece
Petros Kolovos, Democritus University of Thrace, Greece
Katerina Kedraka, Democritus University of Thrace, Greece
Katerina Paleologou, Democritus University of Thrace, Greece
Gregoria Mitropoulou, Democritus University of Thrace, Greece
Electra Stylianopoulou, Democritus University of Thrace, Greece
Kemal Melih Taşkın, Çanakkale Onsekiz Mart University, Türkiye
Çiğdem Şahin Taşkın, Çanakkale Onsekiz Mart University, Türkiye
Fatih Sezer, Çanakkale Onsekiz Mart University, Türkiye
Aslıhan Özbilen, Çanakkale Onsekiz Mart University, Türkiye
Nikolaos Kopsahelis, Ionian University, Greece
Vasiliki Kachrimanidou, Ionian University, Greece
Maria Alexandri, Ionian University, Greece
Aikaterini Natsia, Ionian University, Greece
Aikaterini Papadaki, Ionian University, Greece
Silva Grobelnik Mlakar, University of Maribor, Slovenia
Danijel Davidovic, University of Maribor, Slovenia
Dunja Samec, University North, Croatia
Barbara Medvedec, University North, Croatia
Elif Anda, Mellis Educational Technologies, Türkiye
Caner Anda, Mellis Educational Technologies, Türkiye

EXTERNAL REVIEWER

Prof. Thanassis Karalis, University of Patras, Greece

GRAPHIC DESIGN

Elif Anda

PUBLICATION DATE

2025

DOI

<https://doi.org/10.5281/zenodo.23206793>

COORDINATOR OF THE PROJECT

Democritus University of Thrace, Greece

PARTNER ORGANISATIONS OF THE PROJECT

Çanakkale Onsekiz Mart University - Türkiye, University North – Croatia, University of Maribor - Slovenia, Ionian University - Greece, Mellis Eğitim Teknoloji Ticaret Limited Şirketi, Turkey

LICENSE AND ACKNOWLEDGEMENTS

This work is licensed under a Creative Commons Attribution Non-Commercial 4.0 International (CC BY-NC 4.0) license.
BIOSHIELD - Novel Biotechnological Solutions in Climate Change Mitigation 2024-1-EL01-KA220-HED-000251373 is an Erasmus+ project, funded by the European Union. Views and opinions expressed are, however, those of the author(s) only and do not necessarily reflect those of the European Union or the European Education and Culture Executive Agency (EACEA). Neither the European Union nor EACEA can be held responsible for them.

Table of Contents

Table of Contents.....	3
Abbreviations	6
Glossary	10
Introduction	18
Learning Design for Innovation-Oriented Biotechnology Education.....	19
Purpose and Scope of the Guidebook	19
Climate Change, Disaster Risks and the Role of Biotechnology	20
Educational Technologies Supporting Innovation-Based Learning.....	21
How This Guide Supports Future-Oriented Thinking.....	22
Chapter 1: Bio-based Food and Microbiome Innovations for Climate Resilience	24
1.1. Introduction: Climate Change and the Need for Sustainable Food Systems.....	24
1.2. Microbiome-Based Biotechnology	24
1.2.1. Microbial Biofertilizers and Soil Health	24
1.2.2. Livestock Microbiome Management.....	28
1.2.3. Fermentation-Based Food Production	30
1.2.4. Microbial Waste Valorisation and Circular Bioeconomy.....	32
1.3. Innovation Scenarios.....	34
1.4. Innovation Work Areas for Students.....	35
1.5. Conclusion	39
1.6. Advancing Cultured Meat: A Sustainable Solution for Climate Change	40
1.6.1. The Basics: Why Do We Need Alternatives to Conventional Meat?	40
1.6.2. What is cultured meat, and how is it produced?.....	41
1.6.3. Development of Cultured Meat	42
1.6.4. Major Challenges in Cultured Meat Production	44
1.7. Innovation Work Areas for Students: Advancing Cultured Meat: A Sustainable Solution for Climate Change	51
1.8. Conclusion	55
Chapter 2: Advancing Sustainable Development through Circular Bioeconomy and Resource Efficiency	56
2.1. Introduction: Biotechnology in Sustainable Resource Management.....	56
2.1.1. Current problems and global challenges	58
2.1.2. The role of biotechnology.....	58

2.2. Biorefineries as strategic levers of the bioeconomy.....	58
2.2.1. Understanding biorefineries types and configurations.....	59
2.2.2. Biomass sources and their role in bio-processing.	59
2.2.3. Biomass pretreatment	60
2.3. Spectrum of end-products in biorefineries	62
2.4. Navigating the EU Policy Landscape for the Bioeconomy and Circular Transition.....	63
2.5. Innovation Scenarios and Future Climate Projections	70
2.6. Conclusion	72
Chapter 3: Harnessing Soil Microbiome for Climate-Smart Crop Production and Landscape Management.....	73
3.1. Background Information.....	73
3.2. Applied Microbiome-Based Solutions in Crop Production.....	74
3.2.1. Plant Holobiont as a Functional Unit.....	74
3.2.2. Biofertilisers and Biostimulants.....	75
3.2.3. Formulation of Biofertilisers and Biostimulants.....	79
3.2.4. GIS Analysis of Environmental Factors Influencing the Soil Microbiome in the Context of Climate Change.....	87
3.2.5. Integrating Microbiome-Based Solutions into Climate-Smart Agriculture.....	91
3.3. Innovation Work Areas for Students.....	92
3.4. Conclusion	96
Chapter 4 - Biotechnology for Carbon Capture and Utilisation	98
4.1. Introduction: The Strategic Integration of Biosciences in Climate Mitigation	98
4.2. The Engine of Capture: Biochemical Mechanisms of Photosynthesis.....	99
4.2.1. The Photochemical Phase: Harvesting Energy.....	99
4.2.2. The Calvin-Benson Cycle: The Carbon Fixation Engine	100
4.2.3. The Rubisco Paradox: Evolutionary Flaws and Opportunities.....	100
4.3. Biotechnology-Based Climate Mitigation Strategies through CCU.....	101
4.3.1. Advanced Plant Biotechnology for Climate Mitigation.....	102
4.3.1.1. The Salk Institute's Harnessing Plants Initiative (HPI).....	102
4.3.2. Microbial Systems: Algae and Cyanobacteria.....	103
4.3.3. Carbon Utilisation in the Built Environment	104
4.3.4. Case Studies for Student Analysis	105
4.3.5. Student Research Framework: Methodologies and Protocols.....	108
4.3.6. Policy Framework and Future Outlook.....	112
4.4. Innovation Scenarios and Future Climate Projections	113

4.5. Conclusion	114
Chapter 5: Biotechnology for Ecosystem Restoration and Climate Crisis Mitigation	115
5.1. Nature-Based Solutions for Climate Adaptation	115
5.1.1. Biotechnology Approaches for Ecosystem Restoration and Climate Crisis Mitigation	115
5.2. Innovation Scenarios and Future Climate Projections	119
5.3. Case studies for student analysis	125
5.4. Conclusion	127
Chapter 6: Innovation, Entrepreneurship, and Career Pathways in Climate-Oriented Biotechnology	128
6.1. Climate Innovation and Biotechnology Entrepreneurship	128
6.1.1. How Agricultural Biotechnology is Approached in the Greece, Croatia, Slovenia, and Türkiye	128
6.2. Developing Biotech Startups for Climate and Disaster Solutions	129
6.2.1. Feasibility	130
6.2.2. Competitiveness	133
6.2.3. Product Development and an Interdisciplinary Approach	134
6.2.4. Why Now?	135
6.2.5. Transversal Skills	135
6.2.6. Human and System Perspective	137
6.2.7. Exemplary Agrobiotech Initiatives	137
6.3. Conclusion	140
Beyond the Bench	141
A Closing Call to Action for the Climate-Driven Biotechnologist	141
What this guidebook has asked of you	141
The agricultural biotechnologist as a climate actor	142
A note on uncertainty — and why it matters	142
Your role in the European green transition	143
References	144

Abbreviations

Table 1. Abbreviations

Abbreviation	Full Form
ACC	1-Aminocyclopropane-1-Carboxylate (deaminase)
ACE	Action for Climate Empowerment
AD-bMSC	Adipose-Derived Bovine Mesenchymal Stem Cell
AI	Artificial Intelligence
AMF	Arbuscular Mycorrhizal Fungi
ARSO	Slovenian Environment Agency
ATP	Adenosine Triphosphate
BIQ	Bio-Intelligent Quotient
Bio-CCU	Biotechnology for Carbon Capture and Utilisation
BNF	Biological Nitrogen Fixation
bMSC	Bovine Mesenchymal Stem Cell
CAM	Crassulacean Acid Metabolism
CAN	Calcium ammonium nitrate
CAP	Common Agricultural Policy
CBE JU	Circular Bio-based Europe Joint Undertaking
CCM	Carbon Concentrating Mechanism
CCS	Carbon Capture and Storage (Point-Source)
CCU	Carbon Capture and Utilisation
CDR	Carbon Dioxide Removal
CETCH	Crotonyl-CoA / Ethylmalonyl-CoA / Hydroxybutyryl-CoA (cycle)
CH ₄	Methane
CMC 7	Component Material Category 7 (Microorganisms, EU regulation)
CO ₂	Carbon Dioxide
CRISPR	Clustered Regularly Interspaced Short Palindromic Repeats

Abbreviation	Full Form
DAC	Direct Air Capture
DHMZ	Croatian Meteorological and Hydrological Service
EACEA	European Education and Culture Executive Agency
ECM	Extracellular Matrix
ECR	Enoyl-CoA Carboxylase / Reductase
EM	Effective Microorganisms
ESA	European Space Agency
ETC	Electron Transport Chain
EU	European Union
FAO	Food and Agriculture Organization (of the United Nations)
FBS	Fetal Bovine Serum
FDA	Food and Drug Administration (United States)
G3P	Glyceraldehyde-3-Phosphate
GHG	Greenhouse Gas
GIS	Geographic Information Systems
GMO / GM	Genetically Modified Organism / Genetically Modified
HBA	Hydrogen Bonding Acceptor
HBD	Hydrogen Bonding Donor
HNMS	Hellenic National Meteorological Service
HPI	Harnessing Plants Initiative (Salk Institute)
IAA	Indole-3-Acetic Acid
IEA	International Energy Agency
IoT	Internet of Things
IPBES	Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services
IPCC	Intergovernmental Panel on Climate Change
LAB	Lactic Acid Bacteria

Abbreviation	Full Form
LCA	Life Cycle Assessment / Life Cycle Analysis
LC	Lignocellulosic (Biomass)
MeSH	Medical Subject Headings
MICP	Microbially Induced Calcite Precipitation
N	Nitrogen
N ₂ O	Nitrous Oxide
NADES	Natural Deep Eutectic Solvents
NASA	National Aeronautics and Space Administration
NADP ⁺ /NADPH	Nicotinamide Adenine Dinucleotide Phosphate (reduced)
NCEI	National Centres for Environmental Information
NDVI	Normalised Difference Vegetation Index
NEO	NASA Earth Observations
NREL	National Renewable Energy Laboratory
NUE	Nitrogen Use Efficiency
OECD	Organisation for Economic Co-operation and Development
P	Phosphorus
PBL	Problem-Based Learning
PBR	Photobioreactor
PEP	Phosphoenolpyruvate
PFC 6	Product Function Category 6 (Plant Biostimulants, EU regulation)
2-PG	2-phosphoglycolate
3-PGA	3-Phosphoglycerate
PGPB	Plant Growth-Promoting Bacteria
PGPF	Plant Growth-Promoting Fungi
PGPR	Plant Growth-Promoting Rhizobacteria
PHA	Polyhydroxyalkanoate

Abbreviation	Full Form
PLA	Polylactic Acid
PSI	Photosystem I
PSII	Photosystem II
R&D	Research and Development
Rubisco	Ribulose-1,5-bisphosphate carboxylase/oxygenase
RuBP	Ribulose-1,5-Bisphosphate
SC-CO ₂	Supercritical Carbon Dioxide
SCF	Supercritical Fluid
SCP	Single-Cell Protein
SCFA	Short-Chain Fatty Acids
SDG	Sustainable Development Goal
Smart-MIP	Microbial- and Sensor-Based Integrated Precision (system)
SOC	Soil Organic Carbon
SPAD	Soil Plant Analysis Development (chlorophyll meter reading/index)
TEA	Techno-Economic Analysis
TIBTEC	Trends in Biotechnology
TRL	Technological Readiness Level
TÜİK	Turkish Statistical Institute
UAV	Unmanned Aerial Vehicle
UNFCCC	United Nations Framework Convention on Climate Change
WUE	Water Use Efficiency

Glossary

Table 2. Glossary

MODULES	WORD	EXPLANATION
CHAPTER 1		
1	Microbiome	The community of microorganisms (bacteria, fungi, viruses, archaea) and their collective genomes present in a specific environment, including their interactions with each other and the surrounding environment.
2	Biofertilizer	A substance containing living microorganisms that, when applied to seeds, plant surfaces, or soil, promotes plant growth by increasing the availability of nutrients.
3	Fermentation	A metabolic process in which microorganisms convert sugars and other organic compounds into products such as alcohol, acids, or gases under anaerobic or partially aerobic conditions.
4	Carbon sequestration	The process of capturing and storing atmospheric carbon dioxide (CO ₂) in plants, soils, geological formations, or the ocean to mitigate climate change.
5	Single-cell protein (SCP)	Protein produced from the cultivation of microorganisms (bacteria, yeasts, or microalgae) using low-value substrates, serving as an alternative protein source.
6	Nitrogen fixation	The biological process by which atmospheric nitrogen (N ₂) is converted into ammonia or related compounds, making it available for plant uptake, typically performed by specific bacteria.
7	Methanogenic archaea	Microorganisms belonging to the domain Archaea that produce methane as a byproduct of their metabolism, commonly found in ruminant digestive systems and anaerobic environments.
8	Cultured meat	Meat produced by cultivating animal cells in a controlled laboratory environment, without the need to raise and slaughter animals.
9	Greenhouse gas (GHG) emissions	The release of gases such as carbon dioxide (CO ₂), methane (CH ₄), and nitrous oxide (N ₂ O) into the atmosphere, which contribute to global warming and climate change.

10	Anaerobic digestion	A biological process in which microorganisms break down organic matter in the absence of oxygen, producing biogas (methane) and nutrient-rich digestate.
11	Starter culture	A preparation containing specific microorganisms used to initiate fermentation processes in food production, ensuring consistent quality and safety.
12	Resilience	The capacity of a system to withstand environmental disturbances, adapt to long-term changes, and maintain essential functions under
13	Biogas	A renewable fuel produced through anaerobic digestion of organic matter, primarily composed of methane and carbon dioxide.
14	Scaffold	A three-dimensional structure used in tissue engineering to provide support for cell attachment, growth, and differentiation, essential in cultured meat production.
15	Polyhydroxyalkanoates (PHA)	Biodegradable bioplastics produced by microorganisms as energy storage compounds, used as sustainable alternatives to petroleum-based plastics.
CHAPTER 2		
1	Biorefinery	A facility that integrates biomass conversion processes and equipment to produce fuels, power, and value-added chemicals from renewable biological resources.
2	Circular bioeconomy	An economic model that combines circular economy principles with bioeconomy, focusing on sustainable use of renewable biological resources and waste-to-resource pathways.
3	Biomass	Organic material derived from plants, animals, or microorganisms that can be used as a renewable energy source or raw material for bioproducts.
4	Lignocellulosic biomass	Plant-based material composed primarily of cellulose, hemicellulose, and lignin, such as wood, agricultural residues, and dedicated energy crops.
5	Enzymatic hydrolysis	The breakdown of complex molecules into simpler compounds using specific enzymes, commonly used to convert cellulose into fermentable sugars.
6	Valorization	The process of converting waste materials or by-products into valuable products, adding economic value while reducing

		environmental impact.
7	Life Cycle Assessment (LCA)	A systematic method for evaluating the environmental impacts of a product, process, or service throughout its entire life cycle, from raw material extraction to disposal.
8	Techno-economic analysis	An evaluation method that combines technical performance analysis with economic assessment to determine the feasibility and profitability of a process or technology.
9	Pretreatment	Physical, chemical, or biological processes applied to biomass to break down its complex structure and improve the accessibility of its components for further conversion.
10	Bioplastics	Plastics derived from renewable biological sources or designed to be biodegradable, offering sustainable alternatives to conventional petroleum- based plastics.
11	Cascade processing	A strategy that extracts maximum value from biomass by sequentially processing it for multiple products, prioritizing higher-value applications before energy recovery.
12	European Green Deal	A comprehensive EU strategy aiming to make Europe climate-neutral by 2050 through sustainable economic growth and reduced environmental impact.
13	Farm to Fork Strategy	An EU policy addressing sustainable agriculture, food waste reduction, and circular food system design as part of the European Green Deal.
14	Polylactic acid (PLA)	A biodegradable polymer derived from renewable resources such as corn starch, used in packaging, textiles, and biomedical applications.
15	Industrial symbiosis	A collaborative approach where waste or by-products from one industrial process serve as raw materials for another, creating closed-loop systems.
CHAPTER 3		
1	Plant holobiont	The plant considered together with its associated microbial communities as one functional ecological unit.
2	Plant microbiome	The community of microorganisms associated with a plant, including bacteria, fungi, archaea, viruses, and other microscopic organisms inhabiting roots, shoots, and internal tissues.
3	Soil microbiome	The diverse community of microorganisms living in soil and

		contributing to nutrient cycling, soil fertility, plant growth, and ecosystem functioning.
4	Rhizosphere	The zone of soil directly influenced by plant roots, where intense interactions occur between roots, microorganisms, and soil constituents.
5	Rhizoplane	The root surface that forms the immediate interface between the plant and the surrounding soil environment.
6	Phyllosphere	The aboveground parts of plants, especially leaves and stems, that provide habitat for microbial communities.
7	Endophyte	A microorganism that lives inside plant tissues without necessarily causing disease.
8	Diazotroph	A microorganism capable of fixing atmospheric nitrogen into biologically available forms.
9	Biological nitrogen fixation	The microbial process by which atmospheric nitrogen (N ₂) is converted into ammonia and made available to plants.
10	Biofertiliser	A product containing living microorganisms that improves nutrient availability or nutrient acquisition by plants.
11	Biostimulant	A substance or microorganism applied to plants to enhance nutrient use efficiency, stress tolerance, crop quality, or nutrient availability, regardless of nutrient content.
12	Microbial consortia	Mixtures of multiple microorganisms with complementary functions used to support plant growth, soil functioning, or stress resilience.
13	Effective Microorganisms (EM)	A commercial concept based on mixed microbial inoculants, typically including lactic acid bacteria, photosynthetic bacteria, yeasts, and other beneficial microorganisms.
14	Arbuscule	A highly branched fungal structure formed inside root cortical cells of AMF, serving as the main site of nutrient exchange between plant and fungus.
15	Vesicle	A storage structure formed by some arbuscular mycorrhizal fungi within or between root cells.
CHAPTER 4		
1	Anthropogenic	Environmental pollution and greenhouse gas emissions originating directly from human activity.

2	Bio-Concrete	A sustainable construction material formed through the biological precipitation of calcite by ureolytic bacteria, functioning as a carbon sink.
3	Biopolymer	Naturally occurring complex macromolecules produced by living organisms, such as suberin, which can be highly resistant to degradation.
4	Calvin-Benson Cycle	The light-independent reactions of photosynthesis where chemical energy (ATP and NADPH) is used to fix atmospheric carbon dioxide into organic sugar molecules.
5	Carbon Dioxide Removal (CDR)	The deliberate, large-scale intervention to actively remove carbon dioxide from the atmosphere to achieve "negative emissions."
6	Carboxysomes	Specialized polyhedral protein compartments found in cyanobacteria that encapsulate the Rubisco enzyme, creating a CO ₂ -rich environment to maximize carbon fixation efficiency.
7	Direct Air Capture (DAC)	Technological and engineering methods used to capture carbon dioxide directly from the ambient atmosphere, often storing it in geological reservoirs.
8	Evapotranspiration	The combined process of water evaporation from soil and other surfaces, alongside transpiration from plants, which contributes to the cooling of surrounding environments.
9	Life Cycle Assessment (LCA)	A comprehensive methodology used to evaluate the environmental impacts associated with all stages of a product's, process's, or service's life cycle.
10	Microbially Induced Calcite Precipitation (MICP)	A biochemical process where specific bacteria (e.g., <i>Sporosarcina pasteurii</i>) catalyze the hydrolysis of urea, leading to a localized pH increase and the subsequent precipitation of calcium carbonate.
11	Negative Emissions	A net result achieved when the amount of greenhouse gases removed from the atmosphere exceeds the amount emitted by human activities over a specific period.
12	Photobioreactor (PBR)	An engineered cultivation system, often transparent, designed to optimize the growth of microalgae or cyanobacteria by controlling light, nutrients, and CO ₂ inputs.
13	Photorespiration	An energy-expensive and wasteful metabolic pathway in plants that occurs when the enzyme Rubisco binds with oxygen instead of carbon dioxide, leading to the release of previously fixed CO ₂ .

14	Recalcitrance	The chemical and physical resistance of a biological compound (such as soil organic carbon or suberin) to enzymatic breakdown and microbial decomposition.
15	Rhizosphere	The narrow, dynamic region of soil immediately surrounding plant roots that is heavily influenced by root exudates and supports complex microbial communities.
16	Rubisco	The primary enzyme responsible for carbon fixation in the biosphere; it is notoriously slow and susceptible to binding oxygen instead of carbon dioxide.
17	Suberin	A complex, hydrophobic, and decay-resistant poly-aromatic/poly-aliphatic polyester (commonly known as cork) found in plant cell walls, targeted by biotechnologists for deep soil carbon storage.
18	Synthetic Biology	An interdisciplinary branch of science that involves redesigning organisms for useful purposes by engineering them to have new abilities, such as synthetic carbon fixation pathways.
19	Techno-Economic Analysis (TEA)	A rigorous methodological framework used to analyze and evaluate the economic viability and performance of an industrial process or biotechnological product at scale.
CHAPTER 5		
1	Phytoremediation	The use of plants to remove, stabilize, or transform contaminants in soil, water, or air, offering an environmentally friendly method for site remediation.
2	Bioremediation	The use of living organisms (bacteria, fungi, plants) to break down or neutralize environmental pollutants, restoring contaminated sites.
3	Nature-based solutions	Actions that protect, sustainably manage, or restore natural ecosystems while addressing societal challenges such as climate change and disaster risk reduction.
4	Seed priming	Pre-sowing treatment of seeds with physical, chemical, or biological agents to enhance germination, vigor, and stress tolerance.
5	Phytoextraction	A phytoremediation technique where plants absorb and accumulate contaminants (especially heavy metals) in their above-ground tissues for later removal.
6	In vitro culture	The growth of plant cells, tissues, or organs under sterile, controlled laboratory conditions, used for rapid propagation and conservation.

7	Micropropagation	A tissue culture technique for producing large numbers of genetically identical plants from small plant parts under sterile conditions.
8	Somatic embryogenesis	The production of embryos from somatic (non-reproductive) plant cells, enabling mass propagation and development of improved varieties.
9	Hyperaccumulator	A plant species capable of accumulating exceptionally high concentrations of metals or other contaminants in its tissues without toxicity.
10	Cryopreservation	Long-term storage of biological materials (seeds, tissues, cells) at ultra-low temperatures, preserving genetic diversity for future use.
11	Biopriming	Seed treatment with beneficial microorganisms to enhance germination, plant growth, and disease resistance under field conditions.
12	ACC deaminase	An enzyme produced by certain bacteria that reduces stress-induced ethylene levels in plants, helping them maintain growth under adverse conditions.
13	Phytostabilization	A phytoremediation approach where plants reduce contaminant mobility and bioavailability in soil, preventing spread to groundwater or air.
14	Rhizofiltration	The use of plant roots to absorb, concentrate, and precipitate contaminants from aqueous solutions, used in wastewater treatment.
15	Extracellular polymers	Substances produced by microorganisms outside their cells that help stabilize soil aggregates, improve structure, and enhance water retention.
CHAPTER 6		
1	Climate innovation	The process of developing and implementing new technologies, products, or approaches that address climate change challenges and environmental needs.
2	Feasibility	The assessment of whether a business idea or technology can be practically implemented within reasonable constraints of time, resources, and technical capability.
3	Scalability	The ability of a process, technology, or business model to increase in size or capacity while maintaining efficiency and economic viability.
4	Value chain	The full range of activities required to bring a product from conception through production to delivery to end consumers,

		including design, sourcing, and distribution.
5	Startup	A newly established business, typically technology-driven, designed to develop scalable products or services that address market opportunities.
6	Transversal skills	Transferable competencies applicable across different jobs and sectors, such as critical thinking, communication, collaboration, and adaptability.
7	Design thinking	A problem-solving methodology that emphasizes understanding user needs, defining problems, ideating solutions, prototyping, and testing.
8	Blended learning	An educational approach combining traditional face-to-face instruction with online learning activities and digital resources.
9	Regulatory framework	The system of laws, guidelines, and standards that govern the development, approval, and commercialization of products in specific sectors.
10	Green bioeconomy	An economic system based on sustainable production and use of biological resources, promoting environmental protection and circular resource flows.
11	Proof of concept	An initial demonstration or experiment that verifies a theory or idea has practical potential before full-scale development.
12	Pilot scale	An intermediate stage of development between laboratory research and industrial production, used to test processes under realistic conditions.
13	Interdisciplinary collaboration	Working across multiple academic disciplines or professional fields to address complex problems requiring diverse expertise.
14	Employability	The set of skills, knowledge, and personal attributes that enable individuals to gain and maintain employment in their chosen field.
15	Prototype	An early model or version of a product built to test concepts and learn from them before final development and production.

Introduction

The global community is not only talking about climate change — we are living it. In recent years, extreme weather events have become commonplace, from prolonged droughts in parts of Africa and Europe to flooding that overwhelms infrastructure once considered resilient. These phenomena are not distant possibilities; they are daily realities that threaten food production, economies, and human well-being (Brummer et al., 2011; Spring wheat cultivation trials in drought conditions highlight this urgency). This confluence of environmental stressors, rising sea levels, ecosystem degradation, and unpredictable weather patterns demands solutions that transcend disciplinary silos and traditional scientific boundaries.

Modern biotechnological methods have enabled researchers to engineer crops that maintain yield under drought stress by enhancing root systems and stress-responsive pathways (Tenorio Berrío et al., 2022), and some microbes are now known to significantly improve plant water uptake and resilience under dry conditions (Santander et al., 2024). These are tangible, measurable innovations showing that biological systems can be harnessed to mitigate climate impacts practically and sustainably. Such approaches are aligned with the broader scientific consensus that biotechnology plays a critical role in climate adaptation (Leiva et al., 2025)

This Student's Guidebook was developed with precisely such applications in mind and was intended for upper-level undergraduate students in biotechnology. This guidebook speaks directly to you as a biotechnology student committed to transforming academic knowledge into real-world climate action and stronger community resilience. Instead of presenting biotechnology as an isolated discipline, the guidebook situates it at the intersection of environmental science, policy, innovation, and entrepreneurship, where the real drivers of impact operate. The goal is to nurture a generation of biotechnologists who think systemically, innovate responsibly, and act with purpose, whether in laboratory research, policy planning, or grassroots entrepreneurship.

This ethos is reflected in the BIOSHIELD project, funded by the European Union's Erasmus+ Programme, which brings together academic institutions and an ed-tech organisation from across Europe and Türkiye to bridge the gap between traditional biotechnology education and real-world climate solutions. One of BIOSHIELD's core achievements has been the development of a Higher Education course curriculum specifically designed for students to understand and practice climate-centric biotechnological innovation. This curriculum includes modules which directly address sustainability and resilience in crop systems, a clear example of systemic learning integrated with real challenges.

Throughout this guidebook, you will find case studies based on current research and industry practice, innovation scenarios designed to stretch your creative thinking, and reflective exercises that sharpen critical thinking and problem-solving capabilities. Each chapter is structured to support both individual study and collaborative learning, acknowledging that biodiversity, climate policy, and sustainable biotechnology flourish only through diverse perspectives and interdisciplinary teamwork.

As you work through this guidebook, remember that the most impactful innovations often arise at the boundaries, where biology meets engineering, where science meets society, and where knowledge meets empathy. That is the spirit BIOSHIELD strives to instill, "not just learners, but agents of change prepared to contribute meaningfully to the green bioeconomy of tomorrow".

Learning Design for Innovation-Oriented Biotechnology Education

Effective biotechnology education for climate action takes more than simply teaching the right terms, methods, and laboratory techniques. It also requires learning experiences that will help you think like problem-solvers, who can connect the dots, work with uncertainty, and design solutions that make sense beyond the classroom. For that reason, this guidebook is built around a set of complementary learning design principles that aim to strengthen innovation, systems thinking, and adaptive decision-making.

Problem-Based Learning (PBL) sits at the heart of our approach. Each chapter introduces real-life challenges inspired by climate- and disaster-related contexts, inviting students to work through complex problems that rarely come with a single “correct” answer. Instead of offering ready-made solutions, the guide will encourage you to identify what you do not yet know, explore relevant evidence, test assumptions, and refine your ideas step by step. This mirrors how professional work actually happens—through iteration, collaboration, and learning by doing.

Alongside this, Future-Oriented Thinking is included in the guidebook to help become curious about what is coming next. Climate change is not a fixed problem with a fixed set of tools; it is constantly evolving, and so are the technologies and strategies used to respond to it. Throughout the chapters, you can look ahead, consider emerging risks, and imagine how biotechnology might develop over time—and how those advances could be directed toward meaningful climate solutions.

An Innovation and Prototyping Mindset also shapes the learning activities. You can move from ideas to early-stage solutions by practicing ideation, concept development, and feasibility thinking. Importantly, you can evaluate solutions not only for technical soundness, but also for real-world constraints such as cost, regulation, implementation conditions, and public acceptance. In other words, this guidebook considers innovation as something that must work in practice, not only on paper.

At the same time, the guidebook prioritises Transversal Skills Development, recognising that strong climate action depends on more than technical expertise. Activities are designed to strengthen critical thinking, sustainability awareness, collaboration, communication, and entrepreneurial attitudes. These skills help navigate real stakeholder environments—where scientific decisions are shaped by institutions, communities, policy frameworks, and interdisciplinary teamwork.

Purpose and Scope of the Guidebook

At its core, this guidebook aims to introduce you to the role of biotechnology in tackling climate change and reducing disaster risks. The guidebook helps you gain a clear and meaningful understanding of how their field can actively contribute to solving pressing global challenges, examining the scientific principles, real-world applications, and emerging opportunities in climate-focused biotechnology.

In addition to building knowledge, the guidebook places strong emphasis on developing key skills that you, as the future biotechnology professionals, will need. With the help of this book, you can develop a mindset and a strategic point of view to analyse complex environmental challenges from different angles, develop creative biotechnological solutions, assess the practicality and potential impact of these solutions, and communicate these ideas effectively to a wide range of stakeholders. The guidebook also promotes an entrepreneurial way of

thinking, to turn research ideas into practical products and services that can support the growth of a sustainable green bioeconomy.

The content is organised into six thematic chapters, each focusing on a specific area where biotechnology plays a role in climate action. Chapter 1 explores the development of bio-based materials for sustainable and disaster-resilient systems, showing how biotechnology can offer alternatives to fossil-based materials while strengthening infrastructure resilience. Chapter 2 examines the circular bioeconomy and waste reduction, demonstrating how waste streams can be transformed into useful resources through biotechnological processes.

Chapter 3 addresses climate-resilient agriculture and food security through the study of plant–microbiome interactions. It introduces the plant holobiont, shows how microbial communities shape crop performance under different environmental and landscape conditions, and links microbiome-based solutions with simple experimentation and GIS-based spatial analysis. Chapter 4 introduces biotechnology approaches to carbon capture and utilisation, exploring how biological systems can be used to remove carbon dioxide from the atmosphere and convert it into valuable outputs. Chapter 5 focuses on ecosystem restoration, presenting nature-based solutions that are enhanced through biotechnological advances.

The final chapter, Chapter 6, centres on innovation, entrepreneurship, and career pathways in climate-oriented biotechnology. It equips students with the tools and perspectives needed to turn technical expertise into meaningful careers and impactful ventures. Across all chapters, themes of sustainability, ethics, and social responsibility are consistently integrated, ensuring that students develop a well-rounded and socially conscious understanding of biotechnology's role in addressing global challenges.

Climate Change, Disaster Risks and the Role of Biotechnology

Climate change stands as one of the most multifaceted and consequential issues confronting humanity in the 21st century. According to the Intergovernmental Panel on Climate Change (IPCC), there is unequivocal evidence that the Earth's climate is warming, and that human activities, especially the emission of greenhouse gases, are the principal driver of the observed changes since the mid-20th century. (De Abreu et al., 2022). This warming is not limited to increasing global temperatures; it also alters precipitation patterns, intensifies extreme weather events, accelerates sea-level rise, increases ocean acidification, and exerts profound effects on ecosystems and biodiversity worldwide (Wang et al., 2023).

These climatic shifts do more than raise average temperatures. They compound existing disaster risks and generate new vulnerabilities. Coastal communities, for example, are increasingly exposed to storm surges and flooding as sea levels rise, a trend that has been documented in tide gauge and satellite observations. Agricultural regions face heightened risks of crop failure owing to prolonged droughts, heat waves, and shifts in pest distribution. Warming and altered precipitation also increase the susceptibility of forests to wildfires, whereas urban areas grapple with heat island effects, infrastructure stress, and intensified flood hazards (Trenberth, 2010). The interconnected nature of these risks means that disturbances in one system can cascade into others, amplifying the societal and ecological impacts.

Biotechnology offers a powerful and diverse suite of tools to address both the drivers and consequences of climate change. On the mitigation front, biotechnological approaches contribute to the reduction of greenhouse

gas emissions and to the removal of carbon dioxide from the atmosphere. (Edelenbosch et al., 2024). For instance, engineered microorganisms can convert CO₂ into biofuels, biochemicals, and biomaterials, turning waste products into valuable resources (Raza et al., 2022). Enhanced photosynthetic organisms, such as certain strains of algae and cyanobacteria, have been shown to capture carbon more efficiently than their natural counterparts while producing products like biofuels and bioplastics (Sadvakasova, 2023)

Beyond mitigation, biotechnology plays an important role in adaptation and disaster risk reduction. Advances in genetic improvement have led to crops with increased tolerance to drought, heat stress, and pests — traits that are critical for maintaining food security under shifting climate conditions. (Kolur et al., 2024). Tools such as CRISPR/Cas9 enable precise genome editing to develop these resilient varieties. Likewise, bioremediation technologies harness specialized microbes to restore ecosystems degraded by pollution or extreme events, facilitating recovery and enhancing ecosystem services. In material science, bio-based materials, including bio-composites and bio-polymers, offer sustainable alternatives to fossil-derived construction materials and can improve resilience under extreme conditions.

Importantly, the role of biotechnology in climate action extends beyond direct physical interventions to include environmental monitoring, early warning, and assessment capabilities. Biosensors capable of detecting environmental changes with high specificity enable the early detection of pollution events, disease outbreaks, or ecosystem stress. Molecular markers and genomic tools provide powerful methods for tracking species distributions, monitoring ecosystem health, and informing conservation strategies in the face of climate-driven shifts. Genomic surveillance, for example, has been applied to rapidly identify climate-related changes in pathogen and pest populations, supporting proactive management responses (Brzozowski & Mazourek, 2018; Kumar et al., 2024; Williams et al., 2024)

Understanding the complex relationships between climate change, disaster risk, and biotechnology demands a system thinking approach — one that recognizes interactions among environmental, social, and technological factors. Climate impacts do not occur in isolation; they intersect with economic structures, governance capacities, and social inequalities to shape actual disaster outcomes. Similarly, biotechnological interventions must be designed and implemented with attention to their broader socioeconomic, ethical, and ecological contexts to ensure that they contribute positively to resilience and sustainability.

Educational Technologies Supporting Innovation-Based Learning

Innovation-based learning represents a paradigm shift in education, emphasizing creativity, problem-solving, and the practical application of knowledge to develop novel solutions. Educational technologies play a crucial role in facilitating this pedagogical approach by providing tools that engage learners in active, exploratory, and collaborative experiences. Among the diverse range of technological tools available, animation videos have emerged as particularly effective instruments for supporting innovation-based learning. When integrated strategically into blended learning environments, animation videos can transform traditional educational experiences into rich, interactive learning processes that prepare students for the demands of an innovation-driven economy.

Animation videos, unlike static images or text-based materials, can demonstrate processes, illustrate cause-and-effect relationships, and visualise scenarios that would be impossible or impractical to recreate in physical settings. This capability is particularly valuable in innovation-based learning, where students must understand

complex systems, explore multiple perspectives, and envision alternative possibilities. For instance, animation videos can visualise scientific phenomena at molecular or cosmic scales. Furthermore, well-designed educational animations incorporate principles of cognitive load theory, chunking information into digestible segments and using visual and auditory channels to enhance retention and understanding.

The integration of animation videos into blended learning environments creates synergistic opportunities that enhance both the online and face-to-face components of instruction. In blended learning models, animation videos can serve as pre-class materials in flipped classroom scenarios, allowing students to engage with foundational content at their own pace before attending in-person sessions focused on application and innovation. During asynchronous online learning phases, students can access animation libraries that present case studies of innovation, demonstrate research methodologies, or explain theoretical frameworks relevant to their projects. These videos will prepare you to engage more productively in synchronous activities, whether virtual or in-person, where you can collaborate on innovative solutions, receive feedback on prototypes, or participate in design challenges.

Animation videos are essential for the BIOSHIELD project as they can transform complex biotechnology concepts, such as CRISPR gene editing, engineered microorganisms, and biological disaster mitigation strategies, into visually comprehensible learning experiences. Since the project's focus on climate change solutions through biotechnology, animations are expected to effectively illustrate invisible molecular processes, demonstrate how biotech interventions work in ecosystems, and visualize the effects of climate disasters and their biological solutions. Within the project's blended learning framework, these videos will serve as powerful pre-class materials in flipped classroom scenarios, allowing to grasp foundational concepts before engaging in hands-on research and collaborative problem-solving. The animation videos can bridge the gap between abstract scientific theory and real-world application, enhance your engagement with challenging content, accommodate diverse learning styles, and ultimately empower you, as the next generation of biotech professionals, to develop innovative, evidence-based solutions for environmental challenges.

How This Guide Supports Future-Oriented Thinking

The BIOSHIELD Student's Guidebook is designed to prepare biotechnology students not only for current challenges, but also for the uncertainties of a climate-affected future, that could lead to business idea creation. You will be able to think ahead, adapt to change, and imagine how today's knowledge can respond to tomorrow's needs through the structure and learning approach in the book.

Rather than treating climate change as a static issue, the guide presents it as a dynamic process that evolves alongside technology and scientific understanding. You can move beyond memorization and begin anticipating how biotechnological solutions may develop over time and be applied in new contexts.

Each thematic chapter includes future-focused scenarios, encouraging to apply present-day concepts to emerging or hypothetical situations. You can create ideas about how innovations, such as climate-resilient materials or scalable carbon capture systems, might function under future environmental and industrial conditions.

In addition, technological innovation is presented within real policy and market frameworks. By linking scientific solutions to initiatives like the European Green Deal and real-world projects, you will gain insight into how

research moves from the laboratory into society through policy support, entrepreneurship, and industry collaboration.

You can act as an active contributor to future solutions rather than a passive learner. By emphasising empowerment, participation, and responsibility, it supports you to develop as professionals who are prepared to shape the future of biotechnology and contribute meaningfully to the green transition.

Chapter 1: Bio-based Food and Microbiome Innovations for Climate Resilience

1.1. Introduction: Climate Change and the Need for Sustainable Food Systems

Climate change represents one of the most profound challenges to global food security and ecosystem stability in the 21st century. Rising global temperatures, altered precipitation patterns, increasing frequency of extreme weather events, soil degradation, ocean acidification, and biodiversity loss are significantly affecting agricultural productivity and the food supply chain. At the same time, conventional food systems contribute substantially to greenhouse gas (GHG) emissions through fertilizer production, livestock methane emissions, land-use change, intensive irrigation, and energy-intensive processing and distribution. Food systems are therefore both contributors to and victims of climate change. This dual role highlights the urgent need for structural transformation toward systems that are more sustainable, circular, and resilient. Resilience in food systems refers to the capacity to withstand environmental disturbances, adapt to long-term climatic shifts, and maintain food availability, access, and nutritional quality under stress conditions. Bio-based food systems have emerged as a central pillar of sustainable development and bioeconomy strategies worldwide. These systems rely on renewable biological resources—plants, microorganisms, agricultural residues, and organic waste streams—to produce food, feed, energy, and bio-based materials. By integrating ecological processes and circular resource flows, bio-based systems reduce dependency on fossil inputs, enhance biodiversity, and promote long-term environmental stability. Within this transition, microbiomes play a foundational role. The microbiome refers to the community of microorganisms and their collective genomes present in a specific environment, as well as the interactions among these microbes and with their surrounding environment.

Microbial communities regulate essential ecosystem services, including nutrient cycling, carbon sequestration, nitrogen fixation, organic matter decomposition, and disease suppression. Advances in genomics, metagenomics, and systems biology now allow scientists to understand and manage microbiomes intentionally, creating innovative solutions for climate adaptation and mitigation. Harnessing microbiome functions offers transformative opportunities to improve agricultural resilience, reduce greenhouse gas emissions, enhance soil regeneration, develop alternative proteins, and establish circular food production systems.

1.2. Microbiome-Based Biotechnology

In recent years, advances in biotechnology and microbiome science have led to the development of practical applications that support more sustainable agricultural and food production practices. These innovations utilise beneficial microorganisms to enhance soil fertility, improve livestock efficiency, support alternative food production, and enable circular resource use.

1.2.1. Microbial Biofertilizers and Soil Health

Soil is a fundamental component of terrestrial ecosystems and provides the primary medium for plant growth. It is generally structured into three layers: topsoil, subsoil, and parent material (Itelima et al., 2018). The topsoil layer contains a mixture of minerals, air, water, organic matter, and living organisms, such as plant roots, microorganisms, insects, and worms that are essential for plant development (Jangir et al., 2019). Typically, soil consists of approximately 45% minerals, while water and air each account for about 25% of its volume. Organic

matter represents a smaller fraction, usually ranging from 2% to 5%.

Despite its relatively small proportion of organic matter, soil supports an extremely dense and diverse microbial community. A single gram of soil can contain hundreds of millions to billions of microorganisms (Devi, 2022), including bacteria, fungi, actinomycetes, algae, and protozoa. Bacteria are the most abundant group, with populations reaching 10^8 – 10^9 cells per gram of soil, followed by actinomycetes, fungi, and algae (Putrie et al., 2020; Javed et al., 2021). These microorganisms play a crucial role in ecosystem functioning by decomposing organic matter and transforming it into nutrients that plants can absorb, thereby contributing to soil fertility and plant productivity (Griffiths et al., 2021).

Beneficial soil microorganisms are increasingly used in agriculture through the application of biofertilizers. Biofertilizers are biological formulations containing living or dormant microorganisms that colonize the rhizosphere or internal plant tissues. These microbial inoculants—often composed of bacterial, fungal or algal strains—enhance plant growth by improving nutrient availability and influencing soil microbial activity and physicochemical properties (Allouzi et al., 2022).

Biofertilizer microorganisms support plant growth through several mechanisms, including biological nitrogen fixation, phosphorus mobilisation, and potassium solubilization. Many species also produce phytohormones like auxins, gibberellins, and cytokinins that regulate plant growth (Singh et al., 2021). In addition, certain microbes suppress plant pathogens, enhance plant tolerance to abiotic stresses, such as drought, salinity, heat, and flooding, and contribute to resistance against various pests and diseases. Some microorganisms are also capable of detoxifying pollutants present in soil environments (Maćik et al., 2020).

Microorganisms that stimulate plant growth are commonly referred to as plant growth-promoting rhizobacteria (PGPR), while beneficial fungi performing similar functions are known as plant growth-promoting fungi (PGPF). Both groups can significantly improve crop productivity and plant physiological performance.

Fertilisers are essential agricultural inputs for increasing crop yields and meeting global food demand (Kour et al., 2020). While chemical fertilisers provide rapid nutrient availability and immediate productivity gains (Timsina, 2018), their excessive use can lead to environmental problems, such as soil degradation, water contamination, and groundwater depletion (Lal, 2009; Atieno et al., 2020). For this reason, biofertilizers are increasingly promoted as sustainable alternatives. By utilising beneficial microorganisms, they enhance soil health, support nutrient cycling, and offer an environmentally friendly and cost-effective approach to improving agricultural sustainability (Maćik et al., 2020).

Case Study 1: Mycorrhizal Fungi for Drought Resilience

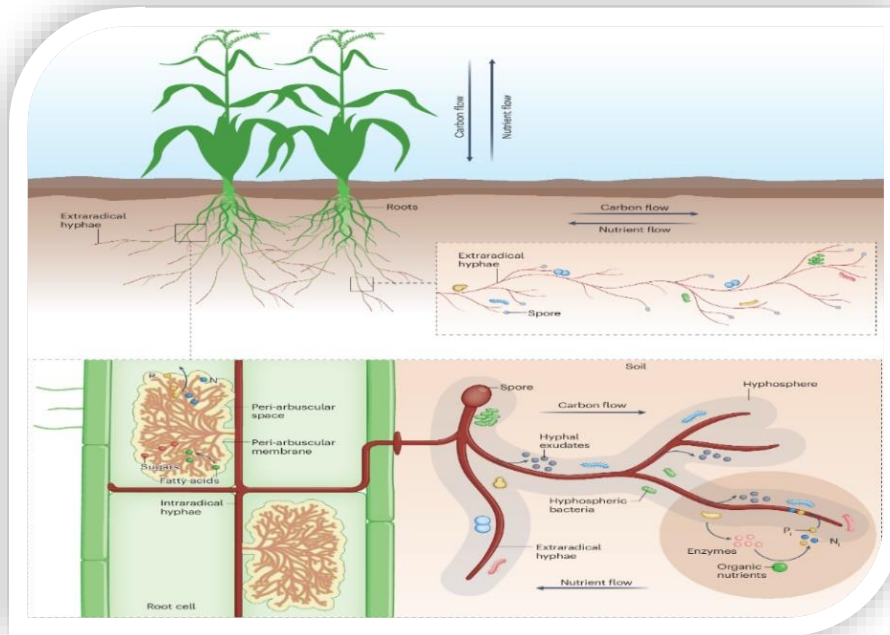


Figure 1. Mycorrhizal fungi extend the root absorption area and improve water and phosphorus uptake (Duan et al. 2024).

Arbuscular mycorrhizal fungi (AMF) (fig. 1) form symbiotic associations with plant roots, extending hyphal networks that improve water and nutrient uptake. Research demonstrates that crops inoculated with these fungi show improved drought tolerance, enhanced phosphorus absorption, and increased biomass under stress conditions. Commercial mycorrhizal inoculants are already used in horticulture, organic farming, and reforestation projects. Their adoption reduces fertiliser requirements, while enhancing soil carbon storage and water retention—key factors in climate resilience.

AMF in Wheat (The Mediterranean Drought Simulation)

- **The Technology:** Inoculation with *Rhizophagus irregularis* (formerly *Glomus intraradices*).
- **The Challenge:** Mediterranean wheat crops face increasingly "flash droughts" during the grain-filling stage, which normally shrivels the kernels.
- **The Innovation:** AMF produces a sticky protein called **Glomalin**, which acts as a "soil glue," improving soil structure and creating micro-pockets that hold water like a sponge.
- **Field/Trial Results:**
 - **Water Use Efficiency (WUE):** Inoculated wheat showed a **25% higher water use efficiency** compared to non-inoculated controls.
 - **Stomatal Regulation:** The fungi signalled the plant to close its stomata (breathing pores) more efficiently, reducing water loss through transpiration without stopping growth.
 - **Yield Retention:** Under severe water stress, AMF-colonised wheat maintained **15–20% higher biomass** than untreated crops.

1.2.1.1. Nitrogen-Fixing Microbial Inoculants

Nitrogen constitutes approximately 78% of the Earth's atmosphere and represents the main natural source of nitrogen available for soil ecosystems. It is an essential element for all living organisms because it forms a key component of many biological molecules, including proteins, nucleic acids, chlorophyll, coenzymes, phytohormones, and various secondary metabolites (Hawkesford et al., 2023). However, most plants are unable to directly utilise atmospheric nitrogen (N_2) because they lack the biochemical mechanisms required to convert it into a biologically usable form, such as ammonia.

This limitation is overcome through the activity of nitrogen-fixing microorganisms present in soil. Various free-living, symbiotic, and associative microbes contribute to the process known as biological nitrogen fixation (BNF) (Mukherjee and Sen, 2021). BNF refers to the enzymatic conversion of atmospheric dinitrogen into ammonia by living organisms, a reaction catalysed by the nitrogenase enzyme complex (Barney and Plunkett, 2022). A wide range of microorganisms, including both aerobic and anaerobic bacteria, as well as cyanobacteria, are capable of performing this process. These nitrogen-fixing organisms are collectively known as diazotrophs (Harding et al., 2022).

Currently, biological nitrogen fixation provides a significant proportion of the nitrogen used in agriculture, accounting for approximately 65% of the nitrogen inputs supporting crop production (Bello et al. 2021). During this process, atmospheric nitrogen is reduced to ammonia through energy-dependent biochemical reactions that require ATP (Lee et al. 2020). Due to its central role in nutrient cycling and soil fertility, BNF is considered a critical component of sustainable agricultural systems.

Case Study 2: Biological Nitrogen Enhancement in Cereal Crops

Recent innovations aim to extend biological nitrogen fixation beyond legumes to cereals, such as maize and wheat. Microbial inoculants containing engineered or naturally efficient nitrogen-fixing bacteria can colonise plant roots and supply part of the plant's nitrogen demand. Field trials have demonstrated reductions in synthetic fertiliser use, while maintaining yield stability. This approach reduces carbon emissions, lowers production costs, and enhances soil microbial diversity. Gene-Edited Diazotrophs in U.S. Corn (Pivot Bio) (<https://www.pivotbio.com>)

- **The Technology:** A commercial product called **PROVEN 40**, which uses gene-edited *Kosakonia sacchari* bacteria.
- **The Challenge:** Natural nitrogen-fixing bacteria usually "shut down" when they sense synthetic fertiliser in the soil.
- **The Innovation:** The bacteria were edited to keep fixing atmospheric nitrogen N_2 into ammonia NH_3 even in the presence of synthetic fertiliser.
- **Field Results (Univ. of Illinois, 2025):**
 - * **Yield Increase:** An average increase of 2–4 bushels per acre.
 - **Replacement Value:** The bacteria successfully provided the equivalent of 35 lbs of nitrogen per acre during early growth.
 - **Conclusion:** It acts as "insurance nitrogen," filling the gaps when synthetic fertiliser is lost to rain or heat.

1.2.2. Livestock Microbiome Management

Methane CH₄ emissions from ruminant livestock represent a critical challenge for global agriculture, acting as a primary driver of atmospheric greenhouse gas (GHG) accumulation. Agriculture generates roughly 62% of anthropogenic CH₄, with ruminants specifically responsible for 58% of that share (Qi, 2025). Within the livestock sector, these animals contribute approximately 81% of total GHG emissions, largely due to microbial activity in the rumen (Harmsen et al., 2019). Data from FAOSTAT (<https://www.fao.org/faostat/en/#home>) further underscore that enteric fermentation is the dominant source of methane within agricultural food systems.

While this process is a natural result of ruminant evolution, the massive scale of modern production has transformed it into a global environmental threat; projections suggest that by 2100, ruminant farming could account for 40%–78% of all global methane emissions (Harmsen et al., 2019). Addressing this is not only ecologically vital, but also economically beneficial, as methane production represents a significant energy drain, wasting between 2% and 12% of an animal's dietary energy. Reducing these emissions is therefore essential for boosting livestock productivity while mitigating climate change. In the livestock production cycle, enteric fermentation accounts for 44% of total GHG emissions. This process occurs in the rumen, a complex fermentation environment where a diverse microbiome breaks down plant polysaccharides into nutrients for the host (Gharechahi et al., 2023).

During this process, methanogenic archaea utilise hydrogen H₂ and carbon dioxide CO₂, byproducts of other microbial fermentation, to produce CH₄. This pathway is functionally necessary to maintain a low-reducing environment, which supports the overall metabolic health of the microbial community. Furthermore, the rumen microbiome's activity is closely tied to the host's physiology, potentially regulating host gene expression *via* short-chain fatty acids (SCFAs). Because of this, researchers are focused on the diversity and community structure of methanogens to find ways to balance feed efficiency with lower emissions. However, because CH₄ production is influenced by a combination of host genetics, physiology, diet, and microbial interactions, a deep understanding of methanogenic metabolic variability is required. Recent efforts to curb CH₄ emissions have explored various avenues, including:

- **Genetic Selection:** Selective animal breeding for low-emission traits (González-Recio et al., 2020).
- **Immunology:** Development of anti-methanogen vaccines (Baca-González et al., 2020).
- **Nutrition:** Implementing dietary management and specialised additives (Haque, 2018).

While these methods show promise, their effectiveness varies, and some risk negatively impacting animal health or growth. Recent evidence comparing high- and low-methane-emitting cattle suggests that long-term solutions lie in the targeted manipulation of the rumen microbiome. Over the last five decades, interventions, such as changing husbandry practices, altering diet composition, and using anti-methanogenic agents, have been studied extensively. Despite this progress, there remains a lack of comprehensive research detailing how these compounds function at the molecular level within methanogenic archaea.

Case Study 3: Rumen Microbiome Manipulation to Reduce Methane

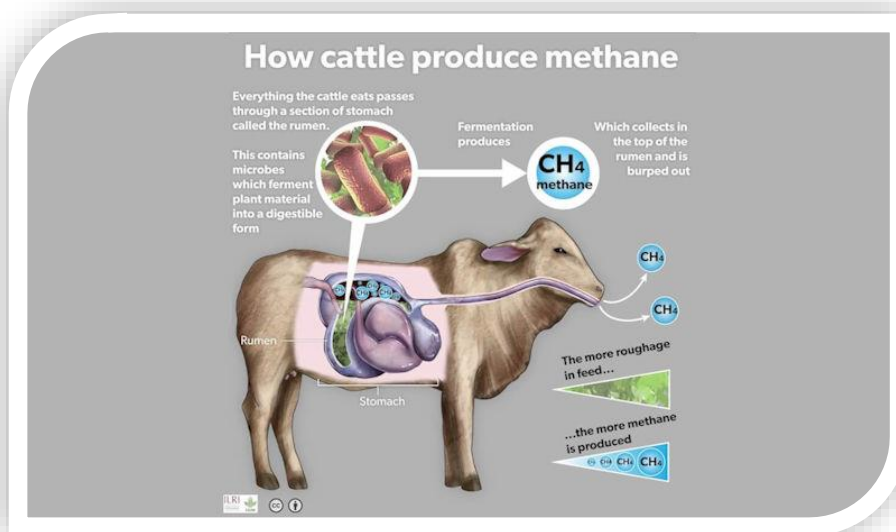


Figure 2. Methane production in the rumen by methanogenic archaea during microbial fermentation (Adapted from the American Society for Microbiology).

Methane is produced in the rumen by methanogenic archaea (Figure. 2). Feed additives, probiotics, and targeted microbiome interventions can alter rumen microbial composition, reducing methane production without compromising animal health or productivity. For example, seaweed-based feed additives have shown promising methane reduction potential by inhibiting methanogenic microorganisms. Such microbiome-focused interventions represent practical mitigation strategies already being piloted in commercial farming.

The "Red Seaweed" Solution (*Asparagopsis taxiformis*) (Roque et al., 2021)

- **The Technology:** Incorporating a small amount (less than 1%) of dried red seaweed into cattle feed.
- **The Mechanism:** The seaweed contains **Bromoform**, which blocks the cobamide-dependent enzyme systems in methanogens.
- Field Results (UC Davis & CSIRO Australia):
 - **Methane Reduction:** Unprecedented results showed up to **80%–90% reduction** in enteric methane when fed to beef cattle.
 - **Productivity:** Steers showed significantly higher weight gain compared to the control group, proving that methane reduction makes "economic sense" by saving energy.
 - **Safety:** Extensive testing confirmed that there were no traces of bromoform in the meat or milk, making it consumer-safe.

1.2.3. Fermentation-Based Food Production

Fermentation represents a resource-efficient, low-capital biotechnology that requires minimal infrastructure beyond basic vessels and raw substrates. While large-scale industrial sectors—such as dairy and brewing—rely on standardised starter cultures for consistency, traditional and domestic fermentation processes often proceed *via* spontaneous microbial action.

The application of fermentation in producing plant-based meat and dairy analogues offers a strategic pathway to mitigating the environmental footprint of food systems. By transitioning away from livestock—particularly ruminants, which are major drivers of land-use change, excessive water consumption, and greenhouse gas (GHG) emissions—these fermented alternatives provide a more sustainable protein source (Poore et al., 2018).

Plant-based analogues of animal protein foods are formulated with refined ingredients or are produced by fermentation with the use of whole plant ingredients. While several life cycle assessments have compared the environmental impact of (fermented) dairy products and their plant-based analogues, a comparison of products that are produced with fermented whole plant ingredients versus formulated refined ingredients is not currently available. Starter cultures suitable for the transformation of plant-based raw materials into analogues of fermented dairy products with appealing textures, taste, and appearances are being developed.

An increasing body of literature assessing the suitability of starter cultures for plant-based analogues of fermented dairy products is becoming available. The poor sensory quality of many current plant-based analogues of dairy products limits their consumer acceptance; however, the use of appropriate fermentation microbes to generate products with improved sensory attributes increases their consumption and thus helps to shift protein intake from an animal-based one to one which is predominantly plant-based, which has been recommended by many food and health institutions (Willett et al., 2019).



Figure 3: Fermented Food

Case Study 4: Precision Fermentation for Alternative Proteins

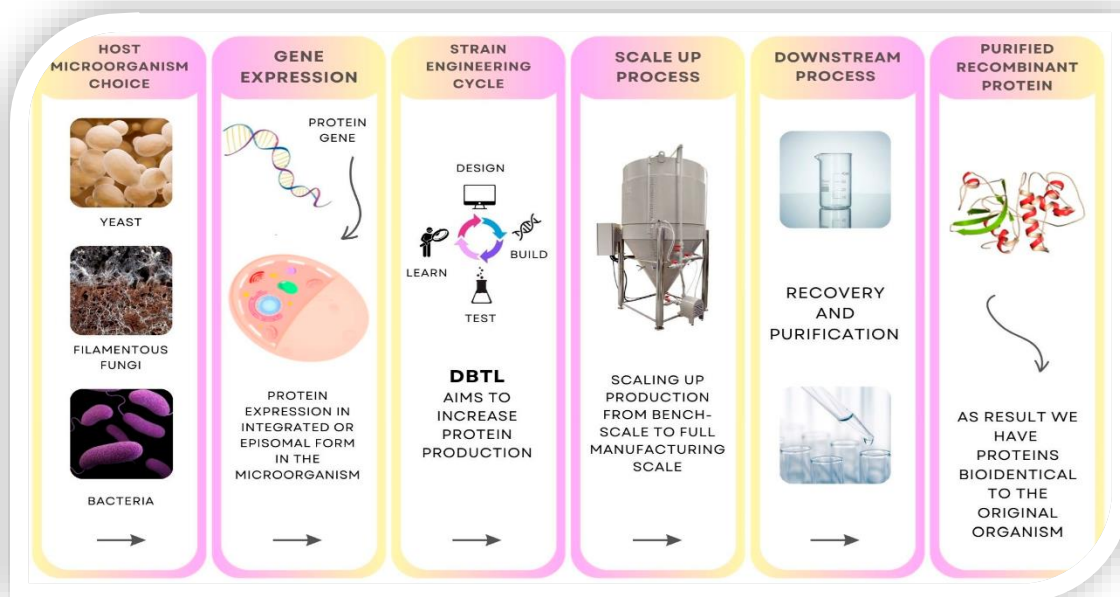


Figure 4. Precision fermentation uses engineered microorganisms to produce specific food ingredients, such as dairy or egg proteins (Knychala et al., 2024).

Precision fermentation uses genetically optimised microorganisms to produce specific proteins, enzymes or fats traditionally derived from animals (Figure. 4). Companies now produce milk proteins, egg proteins, and meat-like compounds using microbial fermentation tanks. Compared to livestock production, these systems require less land, water, and feed while producing fewer greenhouse gas emissions. Fermentation-based proteins, therefore, represent a scalable climate mitigation strategy.

Recombinant Dairy Proteins (Perfect Day) (<https://perfectday.com>)

- **The Technology:** Using the fungus *Trichoderma reesei* to produce Bovine Whey Protein.
- **The Innovation:** Scientists inserted the DNA sequence for cow's milk protein (Whey) into the fungus. When fermented in tanks with sugar, the fungus "expresses" the protein, which is then filtered out.
- **Sustainability Impact:**
 - **GHG Emissions:** Reduces greenhouse gas emissions by **91%–97%** compared to traditional dairy.
 - **Water/Land Use:** Uses 99% less water and 60% less energy.
- **Conclusion:** This technology allows for the production of ice cream and cheese that are identical to dairy, exhibiting the same taste and melting properties, yet are lactose-free and vegan.

1.2.4. Microbial Waste Valorisation and Circular Bioeconomy

Microorganisms possess diverse metabolic capabilities that enable them to degrade organic matter through fermentation processes. Since food waste is rich in organic compounds, such as carbohydrates, proteins, and lipids, fermentation represents an efficient strategy for converting these materials into valuable bioproducts. This strategy contributes to reducing food waste accumulation, while decreasing reliance on landfill disposal and enabling the recovery of useful resources.

Application in Food Science

Building upon these resource recovery strategies, agro-industrial and food processing residues can be valorised for the production of microbial starter and functional cultures used in food fermentation. Many food by-products, such as whey, fruit and vegetable pomace, molasses, and cereal processing residues, contain significant amounts of sugars, proteins, minerals, and other nutrients that can support microbial growth (Gervasi & Mandalari, 2024). These substrates can therefore be used as alternative and low-cost fermentation media for the cultivation of beneficial microorganisms, including lactic acid bacteria (LAB) and probiotic strains. The resulting microbial biomass can be further applied as starter cultures in fermented foods or as functional cultures in the development of functional food products. This approach contributes to the principles of the circular bioeconomy by transforming low-value waste streams into high-value microbial ingredients for the food industry.

Case Study 5: Production of Starter Cultures from Dairy Whey

Whey, a by-product of cheese production, is rich in lactose, proteins and minerals and can serve as an effective growth medium for beneficial microorganisms. Several studies have demonstrated that LAB, such as *Lactiplantibacillus plantarum*, *Lacticaseibacillus rhamnosus*, and *Lacticaseibacillus paracasei*, can be cultivated using whey-based media. The produced biomass can subsequently be used as starter or probiotic cultures for fermented dairy and plant-based foods. This approach simultaneously reduces food industry waste streams and supports the sustainable production of microbial cultures for food fermentation within a circular bioeconomy framework.

Advanced Biopolymers

Agricultural and agro-industrial residues, generated in large quantities globally, present significant environmental and economic challenges if not properly managed. Microbial valorisation has emerged as a sustainable approach for utilising these residues, with bacterial cellulose recognised as a high-value biopolymer due to its high purity, excellent mechanical strength, biocompatibility, and biodegradability (Sharma et al., 2024). Various types of agricultural wastes, including fruit peels, sugarcane bagasse, cereal straw, and corn stover, can serve as low-cost carbon substrates for microbial fermentation, significantly reducing production costs, while supporting the principles of a circular bioeconomy (Belkoshayev et al., 2025; Hasanin et al., 2023). In recent years, advances in strain engineering, synthetic biology, and omics-based metabolic optimisation have significantly enhanced bacterial cellulose yield and enabled the modification of its structural and functional properties. These developments have expanded its potential applications in fields such as food packaging, biomedical materials, cosmetics, and advanced biocomposites (Turganova et al., 2025). Process improvements, including optimised pretreatment strategies, adaptive microbial evolution, and specialised bioreactor systems, contributed to improved scalability and product quality. Integrating bacterial cellulose production into circular bioeconomy frameworks diverts biomass waste from landfills and offers sustainable alternatives to petroleum-based

materials, promoting environmental protection and more efficient resource utilisation (Belkozhayev et al., 2025).

Case Study 6: Anaerobic Digestion



Figure 5. Microbial consortia convert organic waste into biogas and nutrient-rich digestate (Sganzerla et al., 2022).

Anaerobic digestion uses microbial consortia to break down organic waste in oxygen-free environments, producing biogas (methane) and nutrient-rich digestate (Figure. 5). Biogas can replace fossil fuels, while digestate serves as a biofertilizer. This process reduces landfill emissions, closes nutrient loops, and contributes to renewable energy production.

The "Circular City" Model (Magic Dirt, Cenergy USA) (<https://cenergy.us/index.html>)

- **The Technology:** Multi-stage Anaerobic Digesters utilizing a specialized microbial consortium (acidogens, acetogens, and methanogens).
- **The Challenge:** Organic waste in landfills produces uncontrolled methane CH_4 which is 25x more potent than CO_2 as a greenhouse gas. Simultaneously, agriculture needs sustainable fertilisers.
- **The Innovation:** Instead of letting waste rot in the open, it is fed into a sealed "digester." The process is optimised through **Co-digestion** (mixing different waste types, like food scraps and cow manure, to balance the Carbon-to-Nitrogen ratio).
- **Field Results:**
 - **Energy Production:** 1 ton of food waste can generate approximately **300–400 kWh** of electricity, enough to power a home for nearly two weeks.
 - **The "Digestate" Bonus:** The leftover material after fermentation (digestate) is a nutrient-rich bio-fertiliser. Case studies in the US (e.g., *Magic Dirt*) show that this digestate can replace peat moss in horticulture, sequestering more carbon in the soil.
 - **Conclusion:** This creates a closed-loop system: Food waste to Biogas (energy) + Digestate (fertiliser) to new crops

Write your reflection below:

1.3. Innovation Scenarios

Emerging technologies and research directions suggest transformative innovation pathways

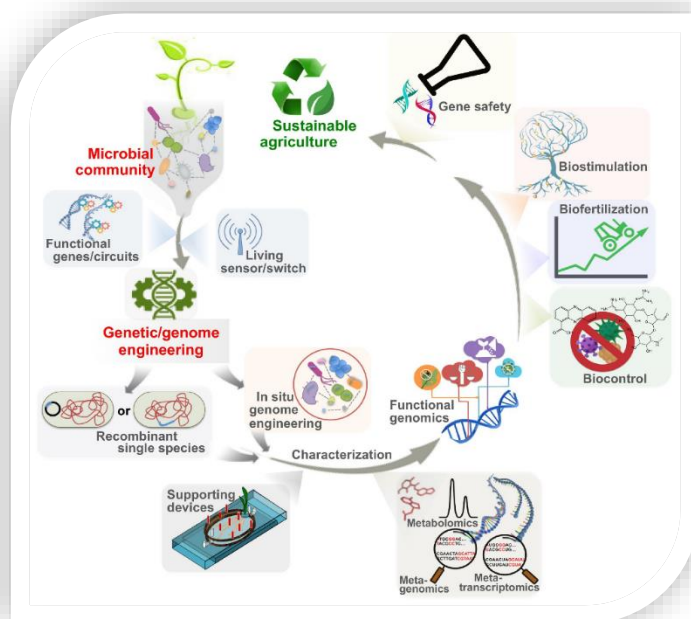


Figure 6. Microbiome engineering approaches for developing climate-resilient agricultural systems (Ke et al., 2021).

for climate-resilient food systems. Advances in microbiome science, synthetic biology, and systems biotechnology are enabling the design of biological solutions capable of stabilising food production under increasingly unpredictable environmental conditions (Figure. 6). One of the most promising directions involves the development of synthetic or “designer” microbiomes. These microbial consortia are intentionally assembled to enhance plant performance by combining strains that promote nutrient uptake, stress tolerance, and disease resistance. Through genome editing and systems biology approaches, scientists are increasingly able to engineer microbial communities that help crops withstand extreme conditions, such as heat stress, drought, salinity, and flooding, thereby improving agricultural resilience in climate-affected regions.

Another emerging innovation concerns the role of soil microbiomes in long-term carbon sequestration. By promoting microbial metabolic pathways that stabilise carbon within soil aggregates, agricultural systems can function not only as food production units, but also as effective carbon sinks. Such approaches strengthen soil structure, increase water retention capacity, and contribute simultaneously to climate mitigation and adaptation strategies. Microbiome-based soil management, therefore, represents a promising strategy for improving both ecosystem stability and agricultural productivity.

In parallel, microbial biotechnology is opening new pathways for sustainable protein production. Alternative protein systems based on microbial biomass, commonly referred to as single-cell protein (SCP), enable the cultivation of bacteria, yeasts, or microalgae using low-value substrates or industrial by-products. Compared with conventional livestock production, these systems require significantly less land, water, and feed resources, while producing substantially lower greenhouse gas emissions. As global demand for protein continues to grow, microbial biomass could provide a scalable and resource-efficient solution.

Finally, fermentation-based food systems offer climate-adaptive solutions for food preservation and production, particularly in regions with unstable energy infrastructure or high ambient temperatures. Fermentation is a low-

energy process that extends shelf life, while enhancing the nutritional and sensory properties of food. Future innovations in starter cultures adapted to higher temperatures and variable environmental conditions could strengthen food security in climate-vulnerable regions, while reducing dependence on refrigeration and energy-intensive processing.

1.4. Innovation Work Areas for Students

Student Innovation Pitch: Project Framework

Use this template to define your vision and technical approach for a climate-resilience project.

Student Innovation Pitch

Project Title & Innovation Track

Proposed Title: *(e.g., Rhizo-Shield: Microbial Consortia for Arid Wheat Cultivation)*

Selected Track: *(e.g., Climate-Adaptive Biofertilizers)*

The Problem Statement

Define the specific climate challenge you are addressing.

Example: "Current nitrogen-fixing fertilisers fail at soil temperatures exceeding 35°C, leading to crop failure during heatwaves in Mediterranean climates."

Your Problem Statement:

The Microbial Strategy (The "How")

Explain the biological mechanism or technological process.

Microorganisms/Substrates:

- Which strains or raw materials will you use?

Process:

Example: *Solid-state fermentation, or spontaneous co-culture*

Your Strategy:

Sustainability & Circularity Metrics

How does this project protect the planet?

Carbon Impact:

- Does it reduce CO₂ or CH₄ emissions?

Waste Reduction:

- Does it utilise a specific industrial byproduct?

Life Cycle Thought:

- What happens to the product at the end of its life?

Why your project matters:

Technical Challenges & Research Goals

What are the "bottlenecks" you need to solve in the lab?

- **Goal 1:** *Isolate a heat-stable strain of Azotobacter.*
- **Goal 2:** *Test tensile strength of the bio-polymer under 80% humidity.*

Your Research Goals:

Goal 1:

Goal 2:

Goal 3:

Impact Pitch

In two sentences, why should a climate-tech company or a university fund this?

Your pitch should highlight: **The innovation** and **the expected impact**

Example: *By 2030, our bio-preservation system could reduce food spoilage by 30% in regions without electricity, preventing the emission of X tonnes of CO2 equivalent, while improving local nutrition."*

Your Impact Pitch:

Use this table to frame your pitch based on your specific areas:

Table 3. Work Area, Problems and Solutions

Work Area	The "Problem"	The "Solution" (The Pitch)
Soil Restoration	Degraded land is losing its ability to grow food and store carbon.	"We are engineering Microbial Consortia that turn dying soil into a carbon-capturing sponge."
Biofertilizers	Synthetic fertilisers are failing under heat stress and killing biodiversity.	"Our Climate-Specific Biofertilizers use local 'extremophile' microbes to keep crops thriving at 40°C."
Food Preservation	30% of food is lost in hot climates due to a lack of electricity.	"We are developing Fermentation-Based Preservation that keeps food safe on the shelf, not in the fridge."
Bio-Packaging	Plastic pollution is permanent, and fossil fuels are depleting.	"We are 'growing' PHA-based packaging that protects food in high humidity and disappears in the soil after use."
Waste-to-Value	Food waste in landfills is a massive methane (CH_4) source.	"Our system uses Microbial Bioconversion to turn 'trash' into high-value animal feed and bioenergy."

1.5. Conclusion

Bio-based food systems supported by microbiome innovations represent a transformative pathway toward climate resilience. Microbial communities underpin essential ecosystem services, from nutrient cycling and soil regeneration to fermentation and waste valorisation. Advances in biotechnology now enable the intentional design and management of these microbial processes. By reducing greenhouse gas emissions, enhancing carbon sequestration, stabilising yields under climate stress, and promoting circular resource flows, microbiome-based solutions address both mitigation and adaptation objectives. However, successful implementation requires interdisciplinary research, supportive governance frameworks, responsible innovation practices, and societal engagement. As climate pressures intensify, the integration of bio-based strategies and microbiome science will play a decisive role in shaping sustainable, resilient, and equitable food systems for the future.

1.6. Advancing Cultured Meat: A Sustainable Solution for Climate Change

1.6.1. The Basics: Why Do We Need Alternatives to Conventional Meat?

Over the past several decades, global demand for animal-derived foods, including meat, dairy, and eggs, has increased steadily due to population growth, urbanisation, and rising incomes in many regions of the world (Godfray et al., 2018; Poore & Nemecek, 2018). Livestock products remain an important source of protein and micronutrients for the human diet; however, conventional livestock production systems are associated with significant environmental pressures. These pressures include greenhouse gases (GHG) emissions, land-use change, water consumption, and biodiversity loss, all of which contribute to global environmental change and climate instability (FAO, 2013; Herrero et al., 2016; IPCC, 2022). Conventional livestock production is estimated to contribute ~0.5°C of global temperature increase over the 21st century, while the demand for meat is expected to grow by 76% until 2050 (Godfray et al., 2018).

One of the most significant impacts of conventional livestock farming is the emission of greenhouse gases. Ruminant animals such as cattle and sheep produce methane (CH₄) during digestion through microbial fermentation processes occurring in the rumen. Methane is a potent greenhouse gas with a global warming potential significantly greater than that of carbon dioxide over short time scales (IPCC, 2006; FAO, 2013). Additional emissions arise from manure management systems, which release both methane and nitrous oxide (N₂O) depending on storage conditions and the treatment practices (IPCC, 2006). Nitrous oxide is also emitted during the use of feed crops and through the application of manure to the soil.

Another major environmental impact associated with livestock production is the change in land use. The conversion of forests and other ecosystems into pastureland or for cultivation areas for feed crop contributes to the emission of carbon dioxide (CO₂) stored in vegetation and soil (Pendrill et al., 2019). When forests are cleared for agricultural use, not only is carbon released into the atmosphere, but most importantly, the capacity of ecosystems to absorb carbon dioxide through photosynthesis is reduced (Curtis et al., 2018). Comparative analyses of food systems have shown that ruminant meat—especially beef—has the highest land-use footprint per unit of protein among major food products (Poore & Nemecek, 2018). Notably, expansion of cattle pasture and soybean cultivation for animal feed has been shown to contribute to tropical deforestation, particularly in regions such as the Amazon basin (Curtis et al., 2018; Pendrill et al., 2019).

Livestock production also affects water resources, as well as biodiversity. The Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES) identified land-use change driven by agriculture as one of the main causes of biodiversity reduction worldwide (IPBES, 2019). Water use in livestock systems occurs both directly, through animal drinking water and farm operations, and indirectly through irrigation required for feed crop production (Poore & Nemecek, 2018). Nutrient runoff from manure and fertilisers can degrade water quality, leading to ecosystem damage of the rivers and coastal environments. Given these challenges, there is growing recognition that meeting the world's rising demand for meat will require not only more efficient but, more importantly, sustainable food production systems. A range of approaches has been proposed to address this challenge: improvements in livestock management practices, improved feed efficiency, improved manure treatment systems, as well as shifts toward plant-based diets or development of plant-based meat alternatives (Godfray et al., 2018).

A more revolutionary approach, cultured meat—also known as cultivated or cell-based meat—has attracted increasing attention as a novel innovation that could produce meat without raising and slaughtering animals. By decoupling meat production from conventional livestock farming, cultured meat technologies are expected

to reduce significantly the environmental footprint of meat production - a recent work suggested that this approach may cut GHGs by 90 % and reduce land use by up to 86 % (Rana et al., 2026)- while maintaining the organoleptic and nutritional characteristics that consumers associate with meat products (Khan et al., 2025, Martins et al., 2024; Stout et al., 2024; Tuomisto & Teixeira de Mattos, 2011; Chriki & Hocquette, 2020).

1.6.2. What is cultured meat, and how is it produced?

Cultured meat is part of a new scientific and industrial field known as cellular agriculture, which encompasses biotechnological approaches for producing animal-derived products directly from cell culture rather than from sacrificing whole organisms (Stephens et al., 2018). Cellular agriculture technologies aim to produce products, such as meat, milk proteins, eggs, and leather, using cell culture systems similar to those used in biomedical research and pharmaceutical companies (Specht et al., 2018).

The production of cultured meat (Figure 6) begins with the extraction of muscle or stem cells from a living animal through a minimally invasive biopsy (Post, 2012; Bhat et al., 2019; Khan et al., 2025; Martins et al., 2024; Stout et al., 2024), the cells are subsequently characterised and cryopreserved. This cell population can be muscle satellite cells, embryonic stem cells, induced pluripotent stem cells, or immortalised tissue-specific cell lines (Soice and Johnston; 2021, Khan et al., 2025; Martins et al., 2024; Stout et al., 2024). The cells are cultured in appropriate medium containing essential nutrients, such as amino acids, glucose, vitamins, minerals, and growth factors that support cell proliferation and multiply rapidly under carefully controlled environmental conditions (Khan et al., 2025; Martins et al., 2024; Stout et al., 2024). Large-scale production of cells requires specialised equipment known as bioreactors, which maintain optimal environmental conditions, such as temperature, oxygen levels, nutrient supply, and waste removal (Humbird, 2021; Wang et al., 2025). Bioreactors allow large quantities of animal cells to grow efficiently while maintaining sterile and controlled conditions.

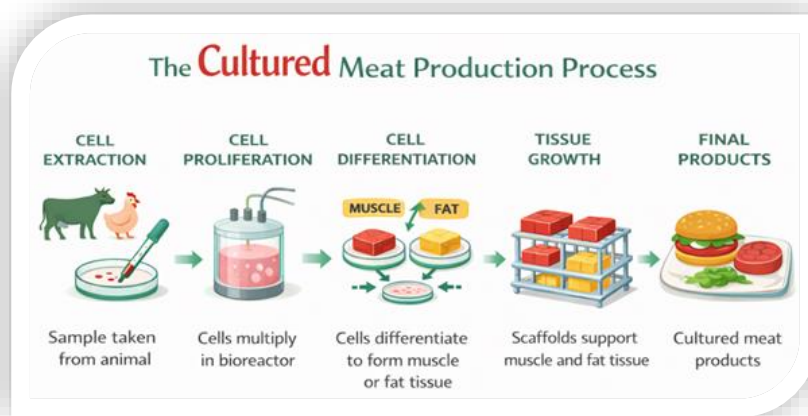


Figure 7. Main steps in cultured meat production: Cell isolation from animal tissue, cell proliferation in culture media, tissue differentiation, growth on edible scaffolds, harvesting and food processing.

Culture media replicate the biochemical environment found in animal tissues and provide the signals required for cell growth and differentiation (Humbird, 2021; Khan et al., 2025; Martins et al., 2024; Stout et al., 2024). Historically, fetal bovine serum (FBS) is widely used as a component of cell culture media because it contains growth factors and hormones required for cell proliferation. However, as in the case of biomedical applications, the use of FBS not only raises ethical concerns but also presents economic limitations due to its high cost. Moreover, the batch-to-batch variability poses a challenge that affects the reproducibility of the culture protocol (Bhat et al., 2019; Garbin et al., 2025; Martins et al., 2024).

Once sufficient cell number has been generated, the cells are induced to differentiate into meat-relevant cell

fates, such as muscle fibres or fat cells, by changing medium composition or through mechanical cues (Khan et al., 2025; Martins et al., 2024; Stout et al., 2024). Cells grow on three-dimensional scaffolds that provide both structural support and support differentiation and guide tissue organisation (Seibert et al., 2025; Khan et al., 2025; Martins et al., 2024; Mariano et al., 2024; Stout et al., 2024). Scaffolds may be composed of edible biomaterials, such as alginate, cellulose, plant proteins, or other biopolymers capable of supporting cell adhesion and tissue formation (Ben-Arye et al., 2020; Bomkamp et al., 2022; Seibert et al., 2025).

After maturation, the cultured tissue can be harvested and processed into food products. Early cultured meat products typically resemble processed meat products, such as burgers or nuggets, although advances in tissue engineering may eventually enable the production of more complex structures, such as steaks or chicken fillets (Risner et al., 2024); however, limitations in size exist without active transport of gases and nutrients.

1.6.3. Development of Cultured Meat

Although cultured meat is often perceived as a modern technological innovation, the concept has surprisingly early intellectual origins. In 1931, Winston Churchill published an essay titled *"Fifty Years Hence"* in The Strand Magazine, in which he speculated about future scientific developments that might transform food production. Churchill suggested that future technological advances could allow humanity to grow edible animal tissues directly without raising entire animals (Figure 8). Although Churchill's vision was speculative, it represents one of the earliest references to the concept underlying modern cultured meat technologies.

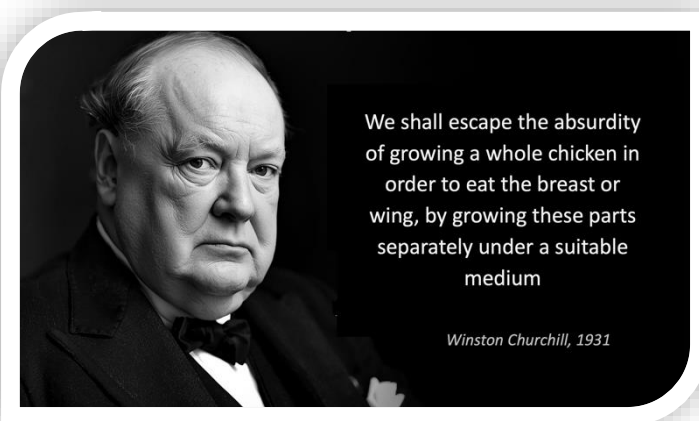


Figure 8. Churchill wrote, "We shall escape the absurdity of growing a whole chicken in order to eat the breast or wing, by growing these parts separately under a suitable medium."

Practical development of cultured meat began much later. The first major milestone occurred in 2013, when researcher Mark Post and colleagues at Maastricht University presented at a news conference the world's first cultured beef burger to a number of chefs who assessed it (Figure 9, Post, 2012). This prototype burger was produced by cultivating muscle fibres derived from bovine satellite cells and assembling them into a burger patty. Although the first cultured burger cost approximately \$300,000 to produce, the experiment demonstrated that producing edible meat from animal cells was technically feasible. Since that time, rapid progress has been made due to improvements in cell culture media, scaffold materials, and bioreactor technologies.



Figure 9. The prototype burger made of cultured meat presented in 2013 in London (BBC News)

The early 2020s marked the beginning of formal regulatory engagement with cultured meat technologies. In 2020, Singapore became the first country to approve a cultured meat product for commercial sale, representing a major milestone in the development of cellular agriculture. Subsequently, in 2022, the United States Food and Drug Administration (FDA) completed its first pre-market consultation for a food product produced using animal cell culture technology (FDA, 2022). Several companies are currently developing cultured meat products using different technological approaches. For instance, GOOD Meat developed cultured chicken that received regulatory approval for sale in Singapore in 2020, while UPSIDE Foods obtained regulatory clearance in the United States for cultured chicken production in 2023 (Good Food Institute, 2025). Meanwhile, Mosa Meat continues to advance cultured beef technologies based on the original research conducted at Maastricht University (Good Food Institute, 2025). At present, a growing number of companies worldwide are working to scale production technologies, reduce manufacturing costs, and improve product quality, which remain critical challenges (see below) for the commercialisation of cultured meat (Wang, 2025; Good Food Institute, 2025).

Cultured meat products are expected to face considerable consumer scrutiny and skepticism upon entering the market (Garcez de Oliveira Padilha, 2022; Verbeke, 2014; Verbeke, 2015). One concern is that some individuals may view these products as ethically questionable because it involves intervening in natural biological processes, sometimes described as “playing God” (Verbeke, 2014). Comparisons have also been made between cultured meat products and genetically modified (GM) foods, which continue to face resistance despite scientific evidence supporting their safety and potential environmental advantages. Another barrier to acceptance relates to organoleptic and sensory qualities, particularly taste and texture (Bryant, 2020; Garcez de Oliveira Padilha, 2022). Although companies, such as Mosa Meat and Aleph Farms reported producing edible cultured beef products, including burgers and steaks, improvements are still required to replicate the characteristics especially of conventional meat (Garcez de Oliveira Padilha, 2022; Verbeke, 2015). Furthermore, cultured meat products are often characterised as “artificial”, “synthetic”, or “fake,” which may discourage consumer acceptance. Studies indicate that initial consumer reactions involve feelings of disgust or perceptions that the product is unnatural (Garcez de Oliveira Padilha, 2022; Verbeke, 2014). However, when participants are provided with more detailed information about the production methods and potential benefits, their attitude tends to become more positive, with concerns shifting toward issues, such as regulatory oversight, safety governance, and accurate product labelling (Bryant, 2020; Garcez de Oliveira Padilha, 2022).

1.6.4. Major Challenges in Cultured Meat Production

Despite the progress made in the past decade, cultured meat production faces several significant challenges (Figure 10). One major issue is the selection and maintenance of cell sources; cells must demonstrate high proliferative capacity, genetic stability as well as the ability to differentiate into muscle and adipose tissues for efficient meat formation (Wang, 2025); adapting cells to the bioreactor culturing conditions- in a suspension instead of the attached on a surface- is also a crucial step that needs improvement. Another key challenge is the development of serum-free and cost-effective culture media, since commonly used components, such as fetal bovine serum, are expensive, ethically controversial and for large-scale food manufacturing due to unstable composition (Wang, 2025). The development of edible scaffolds or microcarriers that support the three-dimensional tissue growth and organisation is also essential to reproduce both the texture and the structure of conventional meat products (Wang, 2025). Integrating cell proliferation, differentiation, tissue structuring, and harvesting into a scalable and economically viable production system continues to be a major barrier to the commercialisation of cultured meat technologies (Wang, 2025)

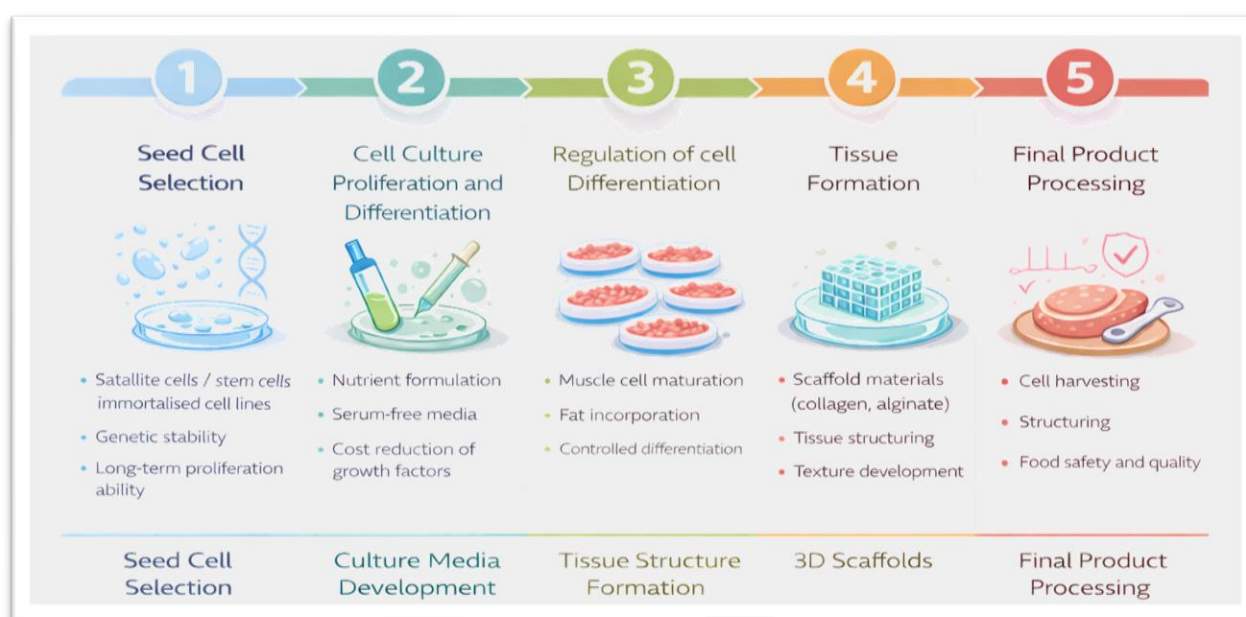


Figure 10. Key technologies and major challenges in cultured meat production.

1.6.4.1. Seed cell selection: Genetic engineering of stem cells to improve cultured meat scalability

A critical technological challenge in cultured meat production is the limited proliferative capacity of animal stem cells, which restricts the ability to generate the large quantities of cellular biomass required for industrial-scale manufacturing (Post, 2012; Zirman et al., 2025). Cultured meat production relies on expanding animal cells *in vitro* to very high densities before inducing their differentiation into tissues, such as muscle and fat, making efficient cell proliferation a central requirement for scalable bioprocessing (Stephens et al., 2018; Zirman et al., 2025). However, many primary animal cells exhibit a finite replicative lifespan in culture, meaning that their capacity for repeated cell division is limited and can constrain the overall yield of cultured biomass (Ben-Arye & Levenberg, 2019).

Bovine mesenchymal stem cells (bMSCs), which are commonly used in cultivated meat research, represent an

attractive cell source because they can differentiate into multiple mesodermal tissues, including myocytes and adipocytes, the two primary components of meat tissue (Zirman et al., 2025). These cells can be isolated from adult tissues and expanded under established cell culture conditions, making them practical for laboratory and industrial applications (Post, 2012; Zirman et al., 2025). However, despite these advantages, bMSCs generally exhibit relatively slow intrinsic growth rates, with doubling times longer than those of pluripotent stem cells, reducing the efficiency of cell expansion during large-scale cultivation (Stephens et al., 2018; Zirman et al., 2025).

In addition to slow proliferation rates, bovine mesenchymal stem cells are prone to replicative senescence after extended culture periods, which further limits their potential for large-scale production (Zirman et al., 2025). Cellular senescence is characterised by irreversible growth arrest while cells remain metabolically active and can result from processes, such as telomere shortening, accumulation of DNA damage, oxidative stress, and activation of tumour-suppressor pathways (Campisi & d'Adda di Fagagna, 2007; Zirman et al., 2025). Once cells enter this senescent state, their ability to divide and contribute to tissue formation is lost, which significantly reduces the efficiency of long-term cell expansion.

The onset of senescence, therefore, represents a major bottleneck in cultured meat manufacturing. When cell populations cease dividing prematurely, the total biomass that can be produced from a culture decreases, requiring frequent cell replacement or repeated cell isolation procedures that increase production complexity and cost (Stephens et al., 2018; Ben-Arye & Levenberg, 2019). Consequently, improving stem cell proliferation rates and delaying senescence are critical objectives in cultivated meat research, as these advances could significantly enhance the scalability and economic feasibility of cell-based meat production systems (Zirman et al., 2025).

Write your reflection below:

Case study 7: Pooled CRISPR screens identify key regulators of bovine stem cell expansion for cultured meat (Zirman et al., 2025)

Strategy

To identify genetic factors that regulate cell proliferation, researchers used a pooled CRISPR-Cas9 knockout screening approach targeting hundreds of genes involved in cell growth and transcriptional regulation. By introducing a library of gene knockouts into stem cells, the experiment allowed cells with beneficial mutations to outcompete others in culture. Sequencing the guide RNA library over time enabled the identification of genes whose disruption improved stem cell expansion.

Results

The CRISPR screening experiment identified TP53 and PTEN as key regulators of stem cell proliferation, with knockout of these genes significantly increasing the growth rate of bovine mesenchymal stem cells and delaying cellular senescence. Gene-edited cells demonstrated faster proliferation and extended culture lifespan compared with non-modified cells. Transcriptomic analysis further showed increased expression of genes associated with cell cycle progression and DNA replication, indicating enhanced proliferative capacity. However, the study also observed reduced adipogenic differentiation potential, highlighting a trade-off between proliferation and differentiation.

Impact

This study showed how genome engineering and functional genomics can be used to optimise cell lines for cultured meat production. By improving the proliferation capacity and lifespan of cultured cells, these strategies could increase biomass yields and reduce production costs. However, the use of genetically modified cells in food systems raises regulatory and safety considerations that must be addressed before commercial implementation.

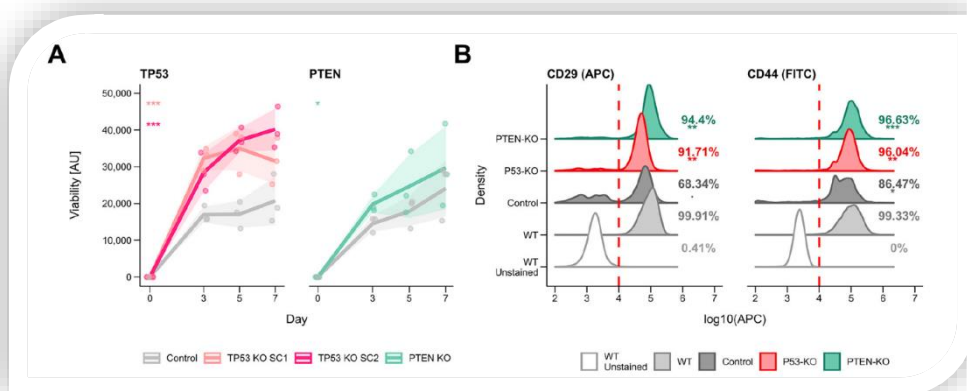


Figure 11. Validation of TP53 and PTEN knockouts in AD-bMSCs.

AD-bMSCs were transfected with Cas9 and an sgRNA targeting either TP53 (red), PTEN (green), or a non-exonic targeting control sgRNA (grey) (n = 3 per group). Cell viability was measured using the Alamar Blue assay at days 3, 5, and 7 after seeding. Both TP53 and PTEN knockout cells exhibited significantly increased viability compared to wild-type (WT) controls. Shaded areas indicate the 95% confidence interval. B Flow cytometry analysis of surface markers CD29 (APC) and CD44 (FITC) in bMSCs. TP53 and PTEN knockout cells maintained surface marker expression levels similar to WT cells, while the control group showed a minor reduction.

1.6.4.2. Cell culture media: serum-free media

Cultured meat production relies on the expansion of animal muscle cells *in vitro*, in controlled environments, where cells are provided with all nutrients and signals necessary for growth, differentiation and tissue formation (Post et al., 2020). One of the most critical components of these systems is the cell culture medium, which supplies essential nutrients, amino acids, vitamins, growth factors, and signalling molecules that regulate cell survival, proliferation, and differentiation (Kolkman et al., 2022). The composition of the culture medium has a central role in determining cell growth efficiency and directly influences the scalability and economic feasibility of cultivated meat production (Stephens et al., 2018).

Traditionally, cell culture media used contain fetal bovine serum (FBS), a widely used supplement that provides a complex mixture of proteins, hormones, attachment factors, and growth factors that support cell attachment and proliferation (Gstraunthaler, 2003). FBS has long been considered a standard component in mammalian cell culture because of its ability to promote robust cell growth and maintain cell viability across a wide range of cell types (Allen et al., 1985).

However, despite its effectiveness, the use of FBS presents significant challenges for cultivated meat production and represents a major barrier to large-scale commercialization: a) it is obtained from the blood of fetuses during the slaughter of pregnant cows, raising substantial ethical concerns contradicting essentially the core objective of producing meat without animal slaughter b) FBS is an ill-defined product- its composition varies between batches and suppliers, and this can lead to inconsistent cell culture performance posing major difficulties in standardization of the process c) the composition variability poses a also a challenge for large scale production systems in which reproducibility and strict quality control are required (Gstraunthaler, 2003; Kolkman et al., 2022; Post et al., 2020; Stephens et al., 2018).

Moreover, FBS represents one of the most expensive components of cell culture media and therefore significantly increases the overall cost of cultivated meat production (Specht et al., 2018). Furthermore, the continued reliance on fetal bovine serum may become unsustainable if cultivated meat production expands and conventional livestock farming declines, leading to supply shortages of this animal-derived material (Kolkman et al., 2022). For these reasons, the development of serum-free and chemically defined culture media has become a key research priority in the cultivated meat field, aiming to improve ethical acceptability, reduce production costs, and enable scalable manufacturing processes (Messmer et al., 2022).

Write your reflection below:

Case study 8: Development of defined media for *in vitro* expansion of primary bovine satellite cells (Kolkmann et al., 2022)

Strategy

Researchers have therefore focused on developing animal-component-free culture media that replace serum with defined mixtures of plant-derived proteins, recombinant growth factors, and synthetic nutrients. These formulations aim to provide the biochemical signals required for cell proliferation and differentiation while eliminating animal-derived ingredients. By designing chemically defined media, scientists can also improve process consistency and enable better control over cellular metabolism and growth.

Results

Experimental studies demonstrated that serum-free formulations can support the proliferation of muscle and stem cells used in cultivated meat production. In some systems, *optimised* media compositions achieved comparable growth rates to serum-containing media while improving reproducibility across batches. Additionally, serum-free systems allow researchers to better understand how specific growth factors and nutrients influence cell *behaviour*, enabling further *optimisation* of cell expansion and differentiation.

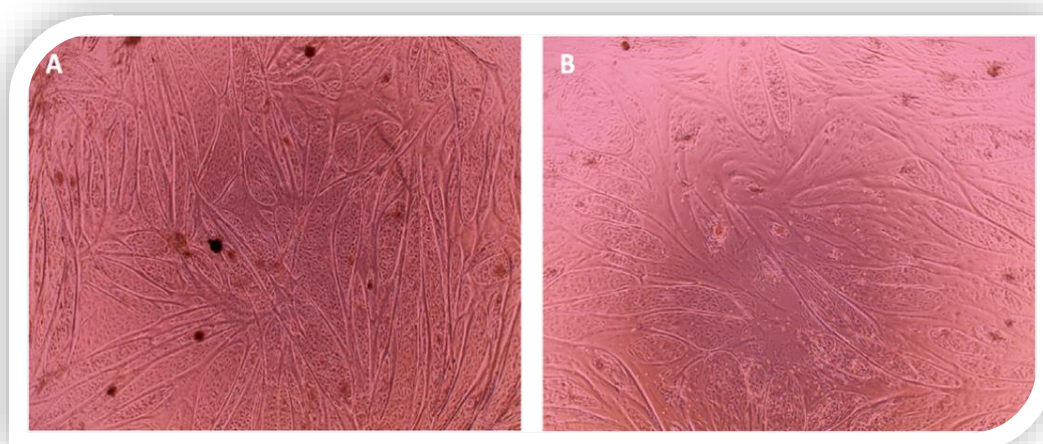


Figure 12. Phase contrast microscopy images of cell differentiation culture at day 7 of differentiation. Cells from two different animals (A & B) that were growing in SFM were seeded for differentiation at—16 population doublings. After 24 h in SFM, when the cells reached 90% confluency, differentiation was induced.

Impact

The development of **animal-component-free and serum-free culture media** is essential for the commercialisation of cultured meat. By reducing reliance on animal-derived inputs, these media formulations improve ethical sustainability, reduce production costs, and support regulatory compliance for large-scale food production.

1.6.4.3. Tissue Formation: development of suitable scaffolding materials

The development of suitable scaffolding materials that support muscle tissue formation and organisation is one of the major challenges cultured meat development faces, limiting its large-scale commercialisation despite its potential environmental and ethical advantages over conventional livestock production (Post et al., 2020; Stephens et al., 2018; Seah et al., 2022). Scaffolds play an essential role in this process because they mimic the extracellular matrix (ECM) and provide structural support for three-dimensional tissue development (Seah et al., 2022).

In conventional meat, muscle fibres are arranged in highly structured and aligned architectures that determine the texture and mechanical properties of meat products (Ben-Arye et al., 2020). Therefore, cultivated meat production requires biomaterials that can promote cell adhesion, proliferation, alignment, and differentiation into functional muscle fibres (Post et al., 2020).

The types of biomaterials currently used for scaffold fabrication pose also a number of limitations (Seah et al., 2022). Many tissue engineering scaffolds are derived from animal-based proteins, such as collagen or gelatin, due to their strong biocompatibility and ability to support cell attachment (Post et al., 2020); however, these materials contradict the sustainability and ethical aims of cultivated meat production because they originate from animal sources (Stephens et al., 2018).

As a result, researchers are exploring plant-derived proteins and other natural biomaterials as alternatives for scaffold design (Xiang et al., 2022). Nevertheless, identifying edible, low-cost, and scalable biomaterials that can support muscle cell growth remains a major challenge in cultivated meat production (Seah et al., 2022).

In addition to material selection, structural complexity and tissue organisation present further difficulties in cultivated meat engineering (Ben-Arye et al., 2020). Natural muscle tissue consists of aligned muscle fibres supported by connective tissue and fat cells that collectively determine the sensory characteristics of meat (Post et al., 2020). To mimic these characteristics, scaffolds must possess appropriate mechanical properties, porosity, and surface features that encourage cell alignment and muscle fibre formation (Singh et al., 2022). Without these structural cues, cultivated meat products may lack the fibrous texture associated with conventional meat, particularly for whole-cut products such as steak or chicken breast (Ben-Arye et al., 2020).

Another critical engineering challenge involves mass transfer limitations within thick tissue constructs (Karande et al., 2004). As muscle tissue grows within scaffolds, oxygen and nutrients must diffuse efficiently throughout the structure to sustain cell viability (Karande et al., 2004). However, thick scaffolds often restrict nutrient diffusion, which can lead to reduced cell growth or the formation of necrotic regions inside the tissue (Post et al., 2020). Designing scaffold structures that allow sufficient nutrient transport while maintaining mechanical stability, therefore, remains an important challenge for cultivated meat production (Seah et al., 2022).

Finally, scaffolds used for cultivated meat must also satisfy food safety, economic, and scalability requirements (Stephens et al., 2018). Unlike biomedical scaffolds that are removed before implantation, scaffolds used in cultivated meat may remain part of the final food product (Seah et al., 2022). Therefore, these materials must be edible, non-toxic, affordable, and suitable for large-scale food manufacturing (Xiang et al., 2022). Developing scaffold materials that simultaneously meet biological, engineering, and food safety requirements remains one of the most significant challenges in the commercialisation of cultivated meat technologies (Post et al., 2020).

Case study 9: Edible films for cultivated meat production (Xiang et al., 2022).

Strategy

To address this challenge, researchers developed **edible biomaterial films derived from plant proteins and polysaccharides** that could function as scaffolds for muscle cell growth. Several materials—including soy protein, glutenin, zein, alginate, chitosan, cellulose nanofibers, and konjac—were fabricated into thin films using food-safe processing methods. Patterned surfaces were produced using **polydimethylsiloxane (PDMS) molds**, creating microgrooved structures designed to guide cell alignment and mimic the organisation of muscle fibres.

Results

Scanning electron microscopy confirmed that the biomaterial films successfully replicated the microstructured patterns of the molds, producing aligned grooves that could guide cell orientation. Cell culture experiments showed that **protein-based films, particularly glutenin and zein**, supported stronger cell adhesion compared with polysaccharide-based materials. Muscle cells cultured on these substrates remained viable, proliferated over time, and developed elongated morphologies characteristic of muscle fibres. Importantly, patterned protein films promoted **aligned myotube formation**, a key step in replicating the fibrous structure of natural muscle tissue.

Impact

This work demonstrates that **plant-derived edible scaffolds can support muscle cell growth, alignment, and differentiation**, providing a promising strategy for producing structured cultivated meat products. Because these materials are food-grade and scalable, they offer a practical approach to improving the texture and structural properties of cultured meat.

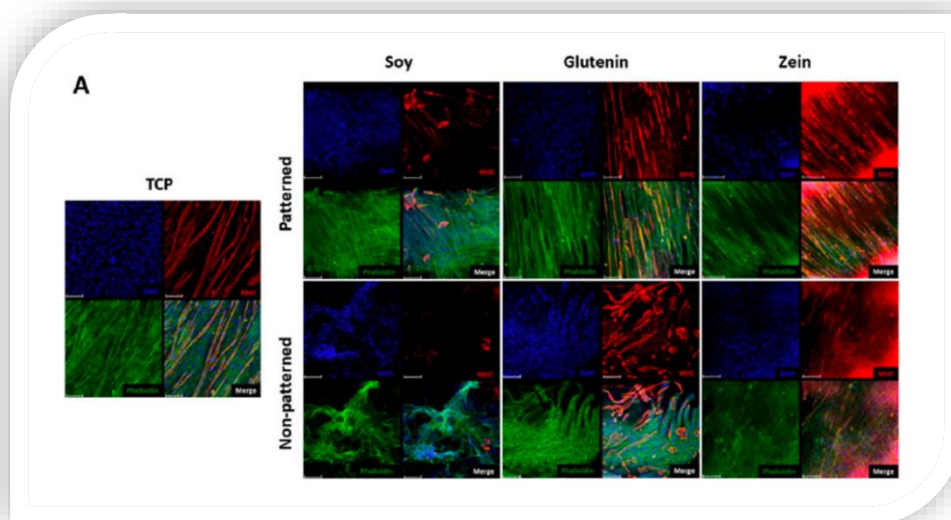


Figure 13. Differentiation C2C12s on various films with and without surface patterns. Differentiated myotubes are marked by immunostaining for MHC and nuclei were stained with DAPI. Colour codes: blue: DAPI; red: Myosin Heavy Chain; Green: phalloidin. TCP: Tissue culture plate Scale bars: 100 μm .

1.7. Innovation Work Areas for Students: Advancing Cultured Meat: A Sustainable Solution for Climate Change

Use this template to define your vision and technical approach for your project.

Student Innovation Pitch

Project Title & Innovation Track

Proposed Title: *(e.g., Plant-derived extracts as alternatives to serum/animal-derived products)*

Selected Track: *(e.g., Cell proliferation & Differentiation)*

The Problem Statement

Define the specific challenge you are addressing.

Example: "Growing global protein demand has accelerated the search for sustainable alternatives to conventional animal products. However, ethical, technical, and economic challenges remain due to the continued use of animal-derived components in production processes, prompting efforts to develop animal-component-free and serum-free systems that improve consistency and meet regulatory standards."

Key questions to consider:

- What problem exists in the current technology?
- Why is it important to solve this problem?
- Who is affected by this challenge?

Your Problem Statement:

The Strategy (The "How")

Explain the scientific approach or technological process you will use.

Materials or Biological Inputs:

- What components will you test or develop?

Example: *Microalgae extracts (e.g., Chlorella vulgaris) as potential growth-promoting supplements.*

- Scaffolds: Which materials will you use?

Experimental Process:

Outline the steps you plan to follow:

- Extraction and characterisation of bioactive compounds
- Formulation of serum-free culture media
- Testing effects on cell proliferation or differentiation

Your Strategy:

Importance

Explain why your project matters for cultivated meat production or biotechnology.

Consider addressing:

- Does your project reduce costs?
- Does it eliminate animal-derived materials?
- Does it improve scalability or sustainability?

Example: *This project could contribute to the development of animal-component-free culture media, helping reduce production costs and improving the ethical and regulatory acceptance of cultivated meat technologies.*

Why Your Project Matters:

Technical Challenges & Research Goals

Identify the key scientific challenges ("bottlenecks") you need to overcome and define your research objectives.

Example goals:

- **Goal 1:** *Identify plant- or algae-derived compounds that support muscle cell proliferation.*
- **Goal 2:** *Evaluate the effectiveness of these extracts compared to conventional serum-based media.*
- **Goal 3:** *Optimise the concentration and formulation for cell growth and differentiation.*

Your Research Goals:

Goal 1:

Goal 2:

Goal 3:

Impact Pitch

In two sentences, why should a biotechnology company or university fund this?

Your pitch should highlight: **The innovation** and **The expected impact**

Example: *Developing affordable, animal-component-free culture media could significantly reduce the cost and ethical barriers of cultivated meat production. This approach may accelerate the transition toward sustainable protein production while improving scalability and regulatory acceptance.*

Your Impact Pitch:

1.8. Conclusion

Life-cycle assessment studies have examined the potential environmental impacts of cultured meat compared with conventional livestock production (Tuomisto & Teixeira de Mattos, 2011; Risner et al., 2024; Blackstone et al., 2025). These studies suggest that cultured meat production could significantly reduce land use requirements as it eliminates the need for large grazing areas and feed crop cultivation. Land currently used for livestock production could potentially be restored as forests or other natural ecosystems, contributing to biodiversity conservation and carbon sequestration. Cultured meat may also reduce greenhouse gas emissions associated with livestock farming, particularly methane emissions from ruminant digestion (Poore & Nemecek, 2018). Therefore, cultured meat represents a potentially transformative innovation that could significantly reduce the environmental pressures associated with conventional livestock production while maintaining access to animal-derived protein.

By producing meat directly from animal cells in controlled environments, cultured meat offers the possibility of lowering environmental impacts while decoupling meat production from large-scale animal farming. However, several technological and socio-economic challenges must be addressed before cultured meat can achieve widespread commercialisation. Major barriers include reducing production costs, replacing animal-derived culture media components with affordable alternatives, and improving the texture and nutritional characteristics of cultivated products. In addition, clear regulatory frameworks and safety assessments are required to support market approval, while consumer acceptance remains a critical factor influencing market adoption. Continued interdisciplinary research across developmental biology, cell and molecular biology, biotechnology, tissue engineering, food science, and bioprocess engineering will play a key role in overcoming these challenges.

Chapter 2: Advancing Sustainable Development through Circular Bioeconomy and Resource Efficiency

2.1. Introduction: Biotechnology in Sustainable Resource Management

Sustainable development confers a long-term framework that integrates environmental protection, economic growth and social equity to ensure a viable future for the forthcoming generations. In view of the increasing climate variability, accelerating resource depletion and widespread environmental degradation, advancing sustainable development necessitates the adoption of strategies that reduce our dependency on finite resources. Meanwhile, economic resilience and social well-being are promoted in the context of strengthening all three interconnected pillars of sustainability: environment, economy and society. Biotechnology contributes significantly to these transitions by facilitating and enabling the efficient, renewable and sustainable valorisation of biological resources.

Traditional linear economic models follow a “take–make–dispose” pattern, a production and consumption trajectory that has been widely critiqued in sustainability studies for promoting excessive resource exploitation, high waste generation and environmental degradation. (Geissdoerfer et al., 2016; Eelager et al., 2025). These linear economy models are incompatible with the current sustainability goals, specifically in sectors that depend on biological resources like agriculture, food production, energy and pharmaceuticals. This misalignment has prompted a flourishing interest in alternative paradigms, focusing on circular economy frameworks that emphasize resource recirculation and life-cycle thinking towards waste minimisation and enhanced resource efficiency (Cahyadi et al., 2024). Evidently, resource efficiency has emerged as a key principle for sustainable development, targeting minimising waste reduction while maximising economic, environmental and social value generation.

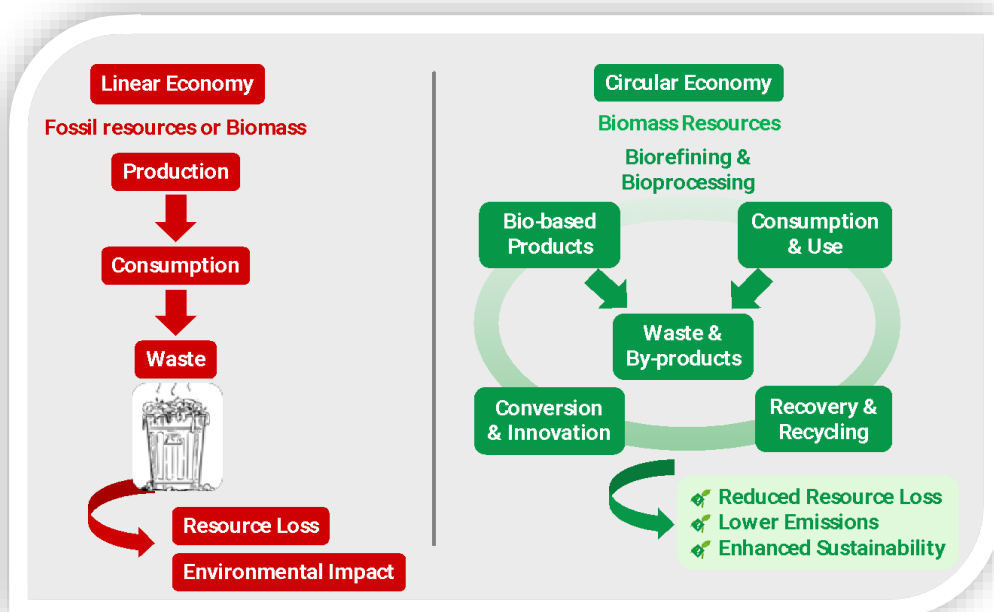


Figure 14. Linear versus Circular Economy

Circular bioeconomy combines both the principles and pillars of circular economy and bioeconomy, as it is aligned and focused on the sustainable use of renewable biological resources, the valorisation of biological waste streams, and the circulation of materials and nutrients within closed-loop systems. Unlike conventional

bioeconomy approaches, which may still rely on linear value chains, the circular bioeconomy prioritises regeneration, cascading use of biomass, and waste-to-resource pathways.

From a biotechnology perspective, circular bioeconomy relies on a range of biological processes including microbial fermentation, enzymatic conversion, anaerobic digestion, and bioprocess optimization, that transform organic residues into valuable products. Microbe and enzyme-mediated systems enable the conversion of agricultural residues and food processing by-products (or other organic materials) into bioenergy, bio-based products and platform chemicals, biomaterials, thereby valorising streams that would be otherwise lost. Biotechnology contributes directly to enhanced resource efficiency and climate mitigation within circular bioeconomy frameworks through improvements in conversion efficiency, reduction in resource losses and the re-utilisation of renewable feedstocks.

In fact, resource efficiency in biotechnology extends beyond the use of raw material, as it includes reduced water and energy consumption, lower GHG emissions, particularly during processing and improved yields via process optimisation. Life cycle analysis (LCA) is applied to assess the environmental performance of bio-based products and bioprocesses, whereas techno-economic analysis evaluates the economic feasibility and the margins of benefit. At the global level, circular bioeconomy supports several Sustainable Development Goals (SDGs), particularly responsible consumption and production, climate action, clean energy, and sustainable industry. For students in the field of biotechnology, understanding these theoretical foundations is essential to further develop and design solutions that are both technically effective and environmentally and socially responsible.



Figure 15. Sustainable Development Goals adopted by the UN

Nonetheless, sustainability challenges are dynamic and constantly evolving. Climate change, population growth, and shifting consumption patterns are affecting both the availability and quality of biological resources. As a result, achieving sustainable development is strongly interconnected with the ability to anticipate future risks and implement adaptive, innovation-driven solutions. This necessitates moving beyond theoretical knowledge towards scenario-based planning and innovation-oriented strategies.

The present chapter confers a thorough learning resource for the Erasmus+ project "Novel Biotechnological Solutions in Climate Change Mitigation.". The material is aimed at both students and educators, and connects

core concepts on circular bioeconomy and sustainable food systems with innovative approaches. In order to comprehend the role of biotechnology in sustainable food systems and climate change mitigation, it is crucial to examine the scientific, environmental and socio-economic foundations that shape modern production systems and agriculture, along with specific challenges.

2.1.1. Current problems and global challenges

- An increasing global population that drives a surge in food demand worldwide.
- Climate change is affecting crop yields through droughts, floods and extreme temperatures.
- Soil degradation and water scarcity influence agricultural productivity.
- Loss of biodiversity entails a reduction in ecosystem resilience.
- Food insecurity and unequal food distribution.
- Supply chain vulnerabilities (e.g. in pandemic).
- High greenhouse gas emissions (GHG) from agriculture and livestock.
- Depletion of fossil resources along with increased plastic generation.
- The growing volume of food waste and agricultural by-products poses serious environmental challenges towards food systems' sustainability.

2.1.2. The role of biotechnology

The management of food waste and post-harvest losses mediates critical challenges to preserve the sustainability of food systems. Meanwhile, renewable biomass resources constitute an underexplored source of nutrients that could be further valorised to generate value-added products and enhance the circular bioeconomy. Biotechnology offers several, multi-faceted and effective approaches through the development of technologies and processes that preserve food quality and reduce spoilage to extend shelf life, whereas at the same time advanced enzyme and fermentation processes can convert food waste and agricultural by-products into valuable products such as bioenergy, biodegradable plastics, biomaterials and platform chemicals. The transformation of waste into useful products via biotechnological approaches provides the potential to minimise environmental impact but also create circular and resource-efficient food systems that support sustainability.

2.2. Biorefineries as strategic levers of the bioeconomy

Circular bioeconomy and sustainability in the European Union can be effectively enabled through the development of integrated biorefineries. Biorefineries confer a central role by transforming renewable biomass sources into a spectrum of products like bio-based chemicals, materials, energy and fuels, based on maximizing resource efficiency and cascading use of biomass. The European Union has established and adopted strategic policy frameworks and legislative initiatives to enable the development and integration of biorefineries. The Bioeconomy Strategy and the Circular Economy Action Plan promote resource efficiency, circularity, and the development of bio-based value chains, while research and innovation programmes such as Horizon Europe and the Circular Bio-based Europe Joint Undertaking provide targeted funding to accelerate technological development and market uptake. When aligned effectively, these frameworks create a supportive environment in which biorefineries can drive the transition towards a competitive, low-carbon, and circular bioeconomy.

The concept of biorefinery was first developed in the late 1990s, in response to the growing awareness on the

depletion of finite fossil resources and environmental pressures. Biorefineries resemble conventional petroleum refining processes but instead implement renewable resources (biomass) while addressing societal, economic and environmental aspects. The International Energy Agency (IEA) Bioenergy Task 42 provides the definition of a biorefinery as “a sustainable facility that converts biomass into a variety of marketable products and energy”. As a matter of fact, the formulation of several high-value products with different market outlets from the same initial feedstock has been shown to support economic viability while reducing waste production. The National Renewable Energy Laboratory (NREL) defines biorefinery as “a facility that integrates biomass conversion and equipment to produce fuels, power and value-added chemicals from biomass”.

In the following sections, this chapter will engage with a short classification of biorefineries, different and primary types of biomass that can be exploited in biorefining but also some of the potential end-products to be generated. Likewise, some specific case studies will be explored and additional information will be provided on the legislative frameworks of the EU regarding Circular Bioeconomy.

2.2.1. Understanding biorefineries types and configurations

Biorefineries can be classified in multiple ways, depending on the diversity of biomass resources, processing technologies, and the products formulated. One common approach relies on feedstock type, which includes sugar and starch crops, lignocellulosic biomass (such as wood and agricultural residues), aquatic biomass (like algae), and organic waste streams. Another classification is focused on the technological platform or conversion pathway employed, including for instance biochemical processes (e.g. fermentation and enzymatic hydrolysis) and thermochemical processes (such as gasification, pyrolysis, and hydrothermal liquefaction). Likewise, biorefineries can be distinguished based on the end products, ranging from biofuels and bio-based chemicals to biomaterials and bioenergy. Actually, modern biorefineries integrate multiple feedstocks and processing pathways in the context of maximising efficiency and producing several high-added value products. This multi-dimensional classification engages students to comprehend the wide variety of biorefining configurations, the potential applications and the challenges associated with each biorefinery type.

2.2.2. Biomass sources and their role in bio-processing.

Biomass is composed primarily of cellulose, hemicellulose and lignin, along with lower fractions of proteins, lipids, extractives and inorganic minerals (known as ash). The relative proportions of the above-mentioned components depend on the biomass type, but also, specifically in plant-based biomass, composition is often affected by cultivation practices and weather conditions. Consequently, the chemical composition of biomass determines the conversion pathways and the spectrum of achievable biorefinery outputs. For instance, carbohydrate-rich biomass (e.g. high cellulose and hemicellulose content) is favourable for fermentation processes to produce bioethanol or other bio-based chemicals, whereas lipid-rich feedstocks (oilseeds or waste cooking oils) are more appropriate for biodiesel production. High lignin content could hinder enzymatic conversion but can provide a potential valorization pathway into aromatic chemicals.

Nonetheless, the heterogeneous nature of biomass, seasonal variability, recalcitrant lignocellulosic structures, and the presence of inhibitors demonstrate substantial technical and economic challenges. Efficient pretreatment, fractionation, and process integration are critical to optimise product yields and ensure sustainable, cost-effective biorefinery operations.

Biotechnological Perspective:

Biomass variability, recalcitrant lignocellulosic composition and inhibitors challenge biorefinery processes. Biotechnology addresses the arising issues via engineered enzymes with enhanced lignin tolerance that can break down rigid structures. Metabolically engineered microbial strains can co-utilise multiple sugar streams (e.g. glucose and xylose) and tolerate inhibitory compounds (such as furfural, 5-hydroxymethylfurfural) generated during biomass pretreatment steps. Techniques and approaches like directed microbial adaptation and holistic biological analysis can support the development of robust strains tailored to variable feedstocks, improving process stability, product yield and the overall feasibility.

2.2.3. Biomass pretreatment

The design of a biorefinery process begins with appropriate pretreatment and/or fractionation of biomass to recover value-added products and enhance its fermentability by microorganisms. Effective biomass valorization requires the selection of suitable pretreatment strategies that enable the separation of its main components while employing green solvents and sustainable processing methods. Pretreatment constitutes the critical first step in liberating cellulose and/or hemicellulose from their complex and rigid lignocellulosic matrix, thereby rendering these components accessible for microbial conversion into high-value biotechnological products such as bioenergy, biochemicals, and bioplastics.

Definition:

Lignocellulosic biomass (LC) consists of three main components: cellulose, hemicellulose and lignin, while other polymers can be present in lower amounts, such as pectins and proteins (Bhatia et al., 2021; Kavitha et al., 2023). The distribution of these components varies greatly and depends on the nature of the biomass. In general, cellulose accounts for 30-60% of total biomass, hemicellulose for 14-40%, while lignin for 7-25%. The following Figure illustrates the major compounds of LC, structure and composition and their functional role.

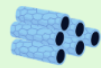
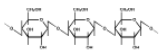
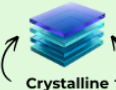
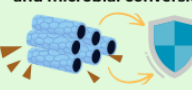
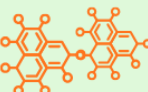
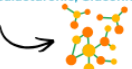
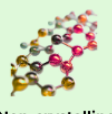
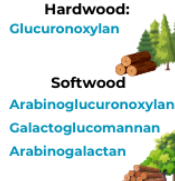
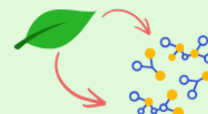
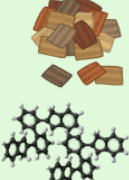
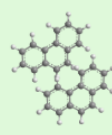
Component	Structure and Composition	Structural Characteristics	Occurrence in Biomass	Functional Role Processing Implications
Cellulose 	Crystalline, linear homopolymer of repeating glucose units β -1,4 glycosidic bonds 	Highly ordered crystalline structure  Crystalline	Present in all lignocellulosic biomass 	Highly resistant to enzymatic hydrolysis and microbial conversion 
Hemicellulose 	Amorphous heteropolymer composed of Hexoses (Glucose, Galactose, Mannose) Pentoses (Xylose, Arabinose) Uronic Acids (Galacturonic, Gluconic) Acetyl groups 	Amorphous branched structure  Non-crystalline	Hardwood: Glucuronoxylan Softwood: Arabinoglucuronoxylan Galactoglucomannan Arabinogalactan 	Readily Degradable (low crystallinity) 
Lignin 	Complex aromatic polymer Monolignol units P-hydroxyphenyl (H)  Syringyl (S)  Guaiacyl (G) 	Highly crosslinked, 3D aromatic network 	Hardwood: S + G Units Softwood Primarily G Units 	Provides structural rigidity & protection Causes enzyme deactivation Reduces cellulose digestibility Delignification essential 

Figure 16. Structural characteristics of LC, composition and functional role.

Biomass pretreatment primarily aims at delignification (lignin separation and/or hydrolysis), followed by defragmentation and partial depolymerization of structural polymers, to increase biomass susceptibility to enzymatic hydrolysis and microbial conversion. Pretreatment technologies can generally be classified into physical, chemical, and enzymatic methods. Often the combination of multiple approaches has been proven advantageous, leading to improved delignification efficiency and enhanced conversion of cellulose and hemicellulose into fermentable sugars.

Although numerous pretreatment strategies have been proposed and evaluated, some of the most promising, both in terms of effectiveness and environmental performance, include ultrasound-assisted processes, microwave, natural deep eutectic solvents (NADES), and supercritical carbon dioxide (SC-CO₂) (Rahmati et al., 2020; Chakraborty et al., 2024).

Principal green pretreatment methods

- **Milling:** Milling is, in most cases, a prerequisite before any other pretreatment method in order to reduce particle size and therefore increase the surface area for the subsequent enzymatic hydrolysis.
- **Ultrasounds:** The use of ultrasounds aims to disrupt the biomass complex structure, exposing its main constituents (cellulose, hemicellulose and lignin) for extraction/hydrolysis. The process is based on acoustic cavitation phenomena: high-frequency sound waves (>20 kHz) pass through a liquid phase, creating cycles of alternating low- and high-pressure. The microbubbles that are created during the high-pressure cycle collapse rapidly, causing localised “hot spots” with high pressure and shear forces that disintegrate biomass cell walls, aiding mass transfers and enzymatic conversion.
- **Microwaves:** It involves the use of an electromagnetic field, causing explosions within the individual biomass particles, facilitating cell wall disruption. The mechanism relies on dielectric polarisation of covalent bonds, causing molecule collision, thereby decomposing the rigid plant cell structure.
- **Natural Deep Eutectic Solvents (NADEs):** Mixtures of compounds comprising a hydrogen bonding donor (HBD) and a hydrogen bonding acceptor (HBA), forming a eutectic mixture with a lower melting point than its individual components. NADEs are highly recognised for their stability, cost-effectiveness, constituting a more environmentally friendly approach to conventional ionic liquids. Certain mixtures of NADEs could effectively solubilise lignin under mild conditions, increasing the enzymatic conversion of cellulose to fermentable sugars, without formation of inhibitory compounds (Satlewal et al., 2018).
- **Supercritical Fluids (SCF):** A supercritical fluid is a compound which is found at a temperature and pressure above its critical point, thereby there is no distinction between a liquid and a gas, presenting the properties of both phases. A supercritical fluid presents the density of a liquid and the viscosity and diffusivity of a gas, acting as an efficient solubilising agent. SCF can be employed for biomass pretreatment either for the recovery of value-added components or to modify the physical structure of the biomass, increase porosity and the subsequent enzymatic conversion.

Enzymatic hydrolysis:

All these aforementioned processes are employed to prepare the LC biomass for the enzymatic hydrolysis, which is required for the conversion of cellulose and/or hemicellulose into fermentable sugars. It should be noted that biomass hydrolysis into sugar monomers can also be carried out chemically; however enzymes comprise a more

eco-friendly approach, while lower amounts of inhibitory compounds are produced, overall enhancing microbial performance. Hemicellulose hydrolysis is carried out by specific enzymes called hemicellulases. The most commonly employed enzymes are endo- β -xylanases and β -xylosidase that hydrolyse xylan into xylo-oligosaccharides and xylose, respectively. For the efficient hydrolysis of cellulose, four enzymes are mainly employed: endoglucanases, cellobiohydrolases, exoglucanhydrolases and β -glucosidases. The combination of these enzymes is required to fully hydrolyse cellulose into its monomer (glucose) (Maitan-Alfenas et al., 2015).

2.3. Spectrum of end-products in biorefineries

Biorefinery development aims to unlock the potential of diverse biomass feedstocks, transforming them into multiple high-value products that advance sustainability, foster a circular bioeconomy and reduce our dependence on fossil resources. One of the key categories is bioplastics and biomaterials, where renewable biomass is converted into biodegradable polymers such as polyhydroxyalkanoates (PHAs) and polylactic acid (PLA) via fermentative processes. These bio-based plastics serve as a sustainable alternative to conventional petrochemical plastics, helping to address the dual challenges of fossil fuel depletion and plastic pollution. The exploitation of agricultural residues, sugars, and other renewable substrates entails the production of materials for packaging, textiles, and composites while reducing dependence on non-renewable resources.



Figure 17. Spectrum of bio-based end-products from biomass in biorefineries

Bioenergy and biofuels represent another major output, including biogas, biodiesel, bioethanol, and emerging fuels like biohydrogen, generated from organic wastes, lignocellulosic residues, and microalgae through biochemical and thermochemical pathways. Energy production is of paramount importance; however, relying solely on bioenergy often restricts economic feasibility, as fuel yields and market prices may not cover operational costs. Integrating high-value outputs, such as food ingredients or pharmaceutical precursors,

alongside bioenergy production can enhance profitability and overall resource efficiency.

In the sector of food and agriculture, biorefineries valorise agro-industrial residues, food waste, and other biomass streams into nutraceuticals, enzymes, organic acids, biofertilisers, and animal feed ingredients. These applications not only add economic value to low-value residues but also promote food sustainability by reducing waste, closing nutrient loops, and supporting more efficient agricultural practices. Overall, these product outlets underscore the massive potential of biorefineries to convert biomass into materials, energy and food-related products, simultaneously addressing environmental, economic, and societal challenges and supporting a sustainable and circular bioeconomy.

2.4. Navigating the EU Policy Landscape for the Bioeconomy and Circular Transition

The EU has developed a comprehensive set of interconnected strategies to guide the transition towards a sustainable, climate-neutral and resource-efficient economy. These frameworks and initiatives on bioeconomy, circular economy, sustainable food systems, biodiversity and climate action work interconnectively to transform how resources are generated, consumed and managed across sectors. These policies do not operate in isolation but confer an integrated system encompassing to reduce environmental impact, enhance resilience, foster innovation and support sustainable growth.

Figure 18 describes how the first EU Bioeconomy Strategy adopted in 2012 was updated in 2018, with the 2022 report assessing implementation and future developments. The European Commission adopted a Bioeconomy Strategy in 2012 to tackle the fossil-based economy, which was further updated in 2018. The updated Strategy reaffirmed the five original objectives: (i) ensure food and nutrition security, (ii) manage natural resources sustainably, (iii) reduce dependence on non-renewable, unsustainable resources, (iv) mitigate and adapt to climate change and (v) strengthen European competitiveness and create jobs.



Figure 18. Development of the EU Bioeconomy Strategy from the first adoption in 2012 to 2018 and 2022 (source: <https://ebcd.org/wp-content/uploads/2022/04/European-Commission-Peter-Wehrheim-PDF-Presentation.pdf>).

These objectives, in line with the targets of the European Green Deal, are now more relevant than ever, following the need to speed up achieving independence on energy 5 and to strengthen food security 6. The EU Bioeconomy Strategy enables a green and equitable transition, covering all three dimensions of sustainability: environment, society and economy.

To reach these objectives, the updated Bioeconomy Strategy was accompanied by a targeted Action Plan along three main action areas:

1. Strengthen and scale up the bio-based sectors, unlock investments and markets;
2. Deploy local bioeconomies rapidly across Europe and
3. Understand the ecological boundaries of the bioeconomy.

Table 4 provides an overview of the key strategies and policy instruments, highlighting the relevance to circular bioeconomy and sustainable food systems.

Table 4. Key EU Strategies and the Relevance to the Circular Bioeconomy

Complete Policy Name	Relevance to Circular Bioeconomy & Sustainable Food Systems
European Green Deal Comprehensive EU Strategy (2019)	Foundation framework for sustainable food systems, circular economy, bio-based industries, emissions reduction in agriculture, and resource efficiency.
Strategies under the Green Deal	
Farm to Fork Strategy (A Strategy for a Fair, Healthy and Environmentally-Friendly Food System) -Sectoral Strategy (2020)	Directly tackles key challenges in sustainable agriculture, food waste reduction, sustainable diets, food labeling, and circular food system design.
Circular Economy Action Plan 2020 (For a Cleaner and More Competitive Europe) -Action Plan	Drives innovation in circular food packaging, food waste minimisation, supports bio-waste valorisation, enhances nutrient recycling, and strengthens sustainable production systems.
EU Biodiversity Strategy for 2030 (Bringing Nature Back into Our Lives) -Environmental Strategy	Supports the transition towards regenerative agriculture, soil health management, agroforestry and ecosystem-based food production models essential for bioeconomy resilience in line with EU sustainability objectives.
Common Agricultural Policy (CAP) 2023–2027 - Regulatory & Funding Framework	Financial backbone for sustainable farming, biomass production for bio-based industries, rural bioeconomy development, and climate-smart agriculture.
EU Bioeconomy Strategy (A Sustainable Bioeconomy for Europe: Strengthening the Connection between Economy, Society and the Environment) - Strategic Policy Framework	Core circular bioeconomy policy linking agriculture, forestry, fisheries, and bio-based industries. Encourages food waste valorisation and bioproduct development.
Circular Bio-based Europe Joint Undertaking (CBE JU) - Public-Private Partnership	Accelerates commercialization of bio-based materials, food by-product valorisation, and rural bioeconomy ecosystems.
8th Environment Action Programme (2021–2030) - Environmental Framework Programme	Provides governance and monitoring framework aligning food system sustainability with EU environmental targets.

Student Activity

You are tasked with designing a sustainable food and bioeconomy project in the EU. How would you leverage existing EU policies and strategies, such as the Farm-to-Fork Strategy, CAP, and the Circular Economy Action Plan, to ensure circularity, environmental sustainability, and economic resilience?



My project design:

Student Activity

Select a case study and design the process-flow chart.

Biotechnology-based Mitigation Strategies through Circular Bioeconomy

The case studies presented in this module illustrate real-world biotechnology applications that support circular bioeconomy principles across different sectors, such as food, feed and energy.

Case study 10: Sustainable and alternative proteins

Overview:

This case explores the production and application of mycoprotein, a fungal protein source grown through industrial fermentation, which has become a globally recognised meat alternative used in a wide range of food products. Mycoprotein demonstrates how microbial biotechnology can provide nutritious food ingredients while significantly reducing environmental impacts compared to conventional livestock protein production. The most widely known commercial example is produced by Quorn Foods, where mycoprotein is the core ingredient in all Quorn products.

The Challenge:

Global demand for protein continues to grow sharply due to population growth and changing dietary patterns, putting pressure on natural resources and traditional livestock systems. Conventional animal agriculture is resource-intensive, requiring high inputs of land, water and feed, and is a significant contributor to greenhouse gas emissions and biodiversity loss. Moreover, within the EU, a strategic need has emerged to diversify and strengthen domestic protein production to improve food security, reduce dependence on imported proteins and support climate and sustainability goals across the food system. To address this, the European Parliament has called for a comprehensive European Protein Strategy that increases availability of sustainably produced proteins and enhances resilience of food supply chains. This strategy is intended to align with broader EU policy objectives such as the Farm to Fork Strategy, Circular Economy Action Plan, and Horizon Europe innovation priorities by promoting sustainable, diversified sources of protein that can reduce environmental impacts and strengthen European food system resilience.

The Biotech Solution:

Mycoprotein production uses fermentation technology to grow the naturally occurring fungus *Fusarium venenatum* in large air-lift fermenters. During fermentation, the organism converts carbohydrates (from maize, wheat or other sugars) into high-quality fungal biomass, rich in protein and fibre. The process is analogous to beer or yoghurt fermentation but on a much larger scale and optimised for protein production. After fermentation, the fungal biomass is processed into a dough-like paste, shaped and prepared into foods that serve as meat alternatives (e.g., mince, fillets, sausages). Mycoprotein is not only sustainable but also nutritionally valuable. It is a complete protein source (containing all essential amino acids), high in fibre, low in saturated fat, and a source of vitamins and minerals. These properties make it a healthy alternative for consumers seeking to reduce meat consumption without compromising on nutritional value.

Case study 11: Transforming marine biomass into functional ingredients

Overview:

This case study focuses on the transformation of invasive marine algae into sustainable and biodegradable functional ingredients for multiple industries. The approach addresses both environmental remediation and sustainable product development. The technology is pioneered by Origin by Ocean, a company specialising in marine biomass valorisation.

The Challenge:

Harmful algal blooms and invasive seaweed species pose serious ecological and economic threats to marine ecosystems, coastal tourism and fisheries. At the same time, many industries rely on fossil-based or environmentally intensive raw materials for surfactants, stabilisers and functional additives. The challenge is to mitigate the negative impacts of excess algae while replacing unsustainable raw materials with renewable alternatives.

The Biotech Solution:

Harvested problematic algae are processed using patented biorefining processes that transform ocean overgrowth into high-performance, bio-based alternatives to ingredients traditionally sourced from fossil fuels, climate-sensitive plants and land- and water-intensive crops.

In particular, valuable compounds such as alginates, fucoidans and functional polymers, can be used in food, cosmetics, detergents, agriculture and packaging applications. Nearly all components of the algal biomass are utilised, exemplifying a zero-waste, circular bioprocess that simultaneously restores marine environments and supplies sustainable industrial inputs.



Figure 19. Invasive Sargassum seaweed accumulation

Case study 12: Biopolymers production from agro-industrial wastes

Overview:

This case study examines the production of bacterial cellulose, a high-performance biopolymer, using agro-industrial waste streams as fermentation substrates. The approach highlights how microbial biotechnology can support sustainable materials development for diverse end-applications. The concept is being advanced by companies such as Polybion (<https://www.polybion.bio/stories/celium-now-globally-available/>).

The Challenge:

The growing demand for textiles, packaging and advanced materials has led to increased use of synthetic polymers and resource-intensive natural fibres. These materials often have high environmental footprints and limited biodegradability. Bacterial cellulose is increasingly used in food systems as a functional ingredient that supports healthier food products. The demand for those products is increasing in parallel with concerns about environmental impact, resource efficiency and public health. Moreover, conventional food texturisers, stabilisers and fat replacers may rely on chemically modified polymers or ingredients with limited nutritional benefits. The challenge lies in producing sustainable, high-performance materials that can replace less sustainable materials in both food and non-food applications while valorising waste biomass.

The Biotech Solution:

Specific bacteria synthesise cellulose nanofibres during fermentation when grown on sugar-rich agro-industrial by-products. The resulting cellulose is highly pure, has water-holding capacity, mechanical strength and biodegradability. In food applications, bacterial cellulose are used as a texturising agent, stabiliser, or fat replacer, enabling formulating clean-label food products without compromising texture or sensory quality. Its use in biotextiles, packaging, composites and biomedical materials demonstrates its versatility. By integrating waste-derived feedstocks with multifunctional product development, this biotechnological pathway exemplifies circular bioeconomy principles and resource-efficient production.

Case study 13: Sustainable fats for food applications through precision fermentation

Overview:

This case study addresses the use of precision fermentation to produce tailored fats and lipids for food and industrial applications. The technology represents a new generation of biotechnology solutions aimed at decoupling fat production from conventional agriculture. A leading example is Melt & Marble company (<https://www.meltandmarble.com/technology>).

The Challenge:

Traditional fat production from livestock or oil crops is associated with high land use, greenhouse gas emissions and biodiversity loss. In addition, achieving specific functional or nutritional fat profiles through conventional means can be inefficient or environmentally costly. The challenge is to produce fats with desired properties while minimising environmental impact and resource use.

The Biotech Solution:

Through precision fermentation, microorganisms are programmed or selected to synthesise specific lipid structures under controlled conditions. Using renewable feedstocks, the microbes convert simple carbon sources into fats with tailored melting behaviour, texture and functionality, enabling efficient, scalable and sustainable lipid production, offering alternatives for food formulations while supporting resource efficiency.

Case study 14: Bioenergy and sustainable fuels

Overview:

This case study explores the production of microbial oil from waste and residue streams as a sustainable feedstock for renewable diesel. The approach demonstrates how industrial biotechnology can integrate waste valorisation with advanced biofuel production, contributing to climate mitigation and resource efficiency. The initiative is being developed by Neste, a global leader in renewable diesel production (<https://www.neste.com/news/waste-based-microbial-oil-set-to-become-a-raw-material-for-renewable-diesel>).

The Challenge:

Conventional biofuels often rely on vegetable oils or energy crops, which can compete with food production, require significant land and water resources and raise sustainability concerns. At the same time, large volumes of organic industrial by-products and residues remain underutilised or require costly disposal. The challenge is to identify alternative lipid sources that are scalable, sustainable and independent of arable land.

The Biotech Solution:

Oleaginous microorganisms, such as specific yeasts or fungi, are cultivated on waste-derived carbon sources, including industrial side streams and agricultural residues. Through fermentation, these microbes accumulate lipids within their cells, which present properties similar to plant oils.

After extraction, the oil can be refined into renewable diesel using specific industrial infrastructure. This biotechnological pathway enables the conversion of low-value waste into high-value renewable fuel while reducing greenhouse gas emissions and supporting circular bioeconomy principles.

Assessing, evaluating and selecting critical parameters in bioprocess design.

The design of a biorefinery is shaped by a group of interconnected technical, environmental, economic, and policy-related parameters, starting with a deep understanding of biomass composition and biological convertibility. The relative proportions of carbohydrates, lignin, proteins, lipids, and minor compounds determine which microbial or enzymatic platforms can be effectively applied. Moisture content, inhibitors, and contaminants influence pretreatment severity and microbial tolerance, while feedstock variability challenges process stability and strain robustness. The technological readiness level (TRL) of biological processes further examines whether laboratory-scale successes can be translated into reliable industrial operation.

Stemming from these characteristics, appropriate bioconversion pathways must be selected. Fermentation, enzymatic hydrolysis, anaerobic digestion, thermochemical routes, or integrated hybrid systems must align with feedstock properties and desired product streams. Among the substantial biological parameters substrate uptake rates, metabolic yields, inhibitor tolerance, and genetic stability should be considered. Scalability depends on preserving performance under industrial conditions such as high solids loading and non-sterile environments.

Apart from the bioconversions, process efficiency and engineering design mediate a decisive role. Energy balance and heat integration reduce operational costs, while reactor configuration, mixing strategies and optimisation of mass transfer impact productivity and conversion yields. The strategies for water use and

recycling, along with the effectiveness of downstream separation, directly correlate with the environmental impact and the economic viability. Optimised carbon conversion and yield are achieved through the synergy of metabolic performance and process engineering.

Critical Parameters in Biorefining Design	
Feedstock considerations ✓ Biomass availability & seasonality ✓ Biomass composition ✓ Moisture content & contaminants ✓ Conversion efficiency ✓ TRL	Technology Selection ✓ Fermentation vs Enzymatic vs Thermochemical Pathways (or combination) ✓ Conversion efficiency ✓ Process Scalability
Process efficiency ✓ Energy Balance & heat integration ✓ Water use & Recycling Strategies ✓ Carbon conversion & Yield Optimization	Circular Integration ✓ Waste Valorization Pathways ✓ Nutrient Recovery ✓ Industrial Symbiosis & Cascade processing
Environmental & Economy Performance ✓ Life Cycle Assessment & GHG ✓ Land use & Biodiversity impact ✓ Techno-economic evaluation	Policy & Governance ✓ Regulatory clarity & sustainability certification ✓ Subsidies & taxes

Figure 20. Interconnection of critical parameters in biorefining design

Modern biorefineries must also incorporate strong circular integration principles. Waste streams (e.g. from one process) should be valorised through cascade processing, nutrient recovery and industrial symbiosis, ensuring that biomass components are exploited at their highest value prior to considering energy recovery. Engineering approaches are prerequisites to minimise losses, enhance resource utilisation and stabilise multi-product systems.

Evidently, environmental, economic, and governance dimensions shape implementation. Life cycle assessment, greenhouse gas mitigation potential, and techno-economic evaluation shape sustainability performance. Regulations, certification programs and financial incentives affect how quickly the market adopts novel products. Since these parameters interact dynamically, the design of a successful biorefinery relies on a systems-level strategic approach that integrates biotechnology, process optimization and sustainability assessment into a cohesive and robust framework.

2.5. Innovation Scenarios and Future Climate Projections

The bottleneck for biotechnological applications such as biorefineries lies in the difficulty of translating laboratory-scale achievements into actual industrial implementations. Despite the intensive research on the development of robust bioprocesses that rely almost exclusively on renewable resources, their actual industrial relevance remains limited. Generally, the lab developed processes have not been validated at pilot or demo scales, lacking a proof of concept on scalability and feasibility. Moreover, comprehensive LCA, techno-economic analysis along with socio-political evaluations are required to provide a better understanding on economic

viability, environmental performance and societal acceptance of the proposed biotechnological solutions. Likewise, the integration of artificial intelligence (AI) and the Internet of Things (IoT) in bioprocesses could potentially reduce operational costs while improving the efficiency of waste and resource management. Nevertheless, the adoption of innovative financing mechanisms and public-private partnerships could support the creation of effective frameworks that encourage biotechnology-driven solutions.

Therefore, your proposed solution should consolidate the above characteristics, ensuring that your scenario is not only innovative but also truly environmentally benign and scalable. You must also ensure that your proposed biorefineries will be able to operate using heterogeneous and region-specific feedstocks in order to achieve a level of independence from seasonality or narrowly defined raw materials. Metabolic engineering, synthetic biology and computational sciences will play a crucial role in improving bioprocess stability and productivity.

Student Activity

Problem-solving exercise

Design a circular biorefinery system that valorises food industry by-products (e.g. potato processing streams) to produce bioenergy, biomaterials and high-value products for the food industry.

- ✓ Which biotechnological interventions should we prioritise to ensure maximum resource efficiency?
- ✓ How would we balance and assess environmental benefits, cost-effectiveness and societal impact, including food security and waste reduction?

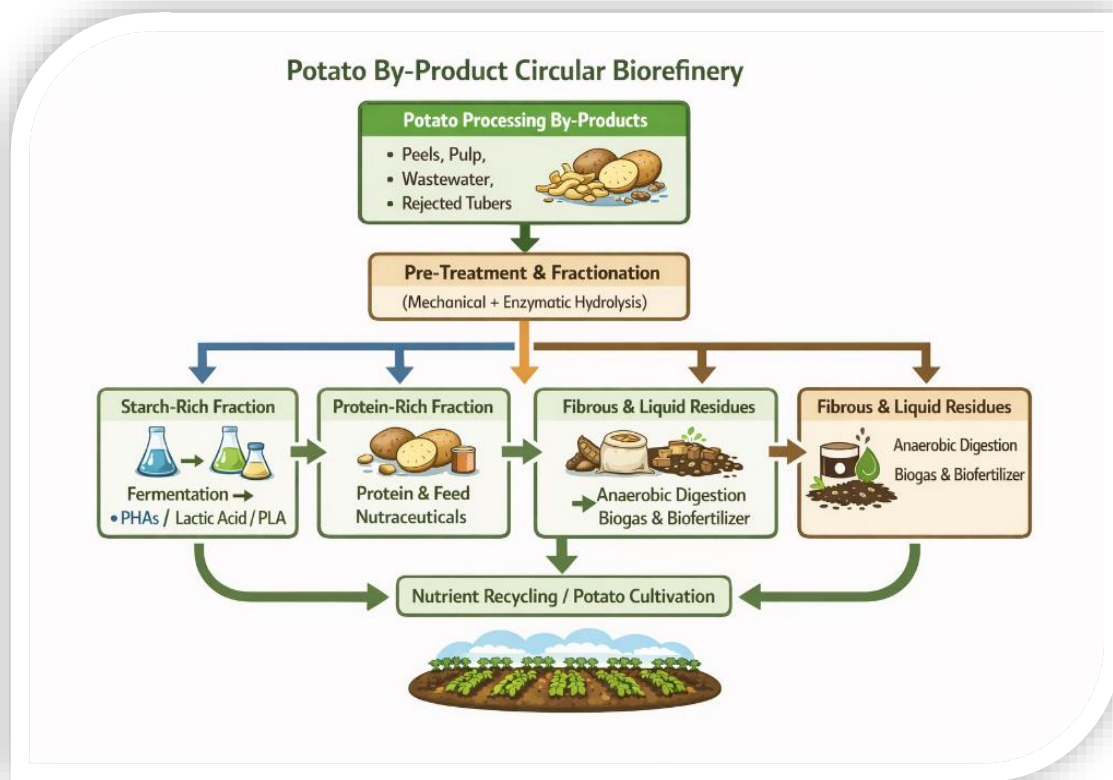


Figure 21. Circular biorefining scenario for potato processing by-products

2.6. Conclusion

Overall, biotechnology plays a pivotal role to advance sustainable development and accelerate the transition towards a circular bioeconomy. Through the integration of innovative bioprocesses, renewable biomass valorisation, and resource-efficient technologies, biorefineries demonstrate promising solutions to the pressing global challenges, like climate change, food insecurity, waste generation, and fossil resource depletion. Circular approaches enable the transformation of agricultural residues, food waste, and other biological resources into value-added bio-based products, energy, and materials while minimizing environmental impact and supporting economic resilience. The successful implementation of these systems requires interdisciplinary knowledge, technological innovation, supportive policy frameworks, and constant evaluation of environmental, economic, and societal impacts. As sustainability challenges continue to evolve, biotechnology and circular bioeconomy approaches will play an important role to create more sustainable, low- carbon, and resource-efficient food and production systems that foster the Sustainable Development Goals and the European Green Deal.

Chapter 3: Harnessing Soil Microbiome for Climate-Smart Crop Production and Landscape Management

3.1. Background Information

Global food production is facing unprecedented pressure due to a combination of demographic, environmental, and socio-economic challenges. The global population is projected to reach approximately 9.5 billion by 2050, significantly increasing the demand for food, feed, and bio-based resources. At the same time, an estimated over 700 million people currently experience chronic hunger, while projections suggest that this number could approach 840 million by 2030 if current trends continue. These challenges must be addressed despite the limited availability of arable land, which is increasingly constrained by soil degradation, urbanisation, and climate change.

To meet rising demand, modern agriculture has become highly dependent on external inputs, particularly synthetic fertilisers. While these inputs have enabled substantial yield increases, they are associated with low nutrient use efficiency, as crops typically utilise only 30–40% of applied nutrients, with the remainder lost to the environment. These losses contribute to greenhouse gas emissions, water pollution, eutrophication, and long-term soil degradation. In addition, the production of synthetic fertilisers is highly energy-intensive and depends on non-renewable resources such as natural gas and phosphate rock, making agricultural systems vulnerable to resource scarcity and geopolitical instability.

These limitations have intensified the search for more sustainable and resilient agricultural practices. In this context, biological solutions are gaining increasing attention. Biofertilisers and biostimulants are emerging as key tools to improve nutrient efficiency, enhance plant resilience, and reduce reliance on synthetic inputs. This shift is reflected in the rapid expansion of global markets. The biofertiliser market is projected to reach approximately 3–5 billion USD within the next decade, while the biostimulant market is expected to exceed 6–10 billion USD, driven by technological innovation, regulatory pressures, and the need to adapt agriculture to climate change.

A central component of these biological approaches is the soil microbiome. Soil microorganisms regulate essential processes such as nutrient cycling, organic matter decomposition, and plant–soil interactions, thereby directly influencing plant growth and ecosystem functioning. By enhancing biological nitrogen fixation, phosphorus mobilisation, and plant stress tolerance, the soil microbiome offers significant potential for improving both productivity and sustainability in agricultural systems.

Importantly, these processes are not uniform across space but are shaped by environmental variability at the landscape level. Soil properties, climate conditions, topography, and land use interact to determine the composition and functioning of soil microbial communities. Understanding these spatial patterns is essential for developing targeted and efficient management strategies. In this context, Geographic Information Systems (GIS) and spatial analysis provide powerful tools for linking soil microbiome processes with landscape-level decision-making and precision agriculture.

This chapter explores how the soil microbiome can be harnessed to support climate-smart crop production and sustainable landscape management. It integrates biological, agronomic, and spatial perspectives, providing a foundation for understanding how plant–microbe interactions can contribute to resilient, resource-efficient, and

environmentally sustainable food production systems.

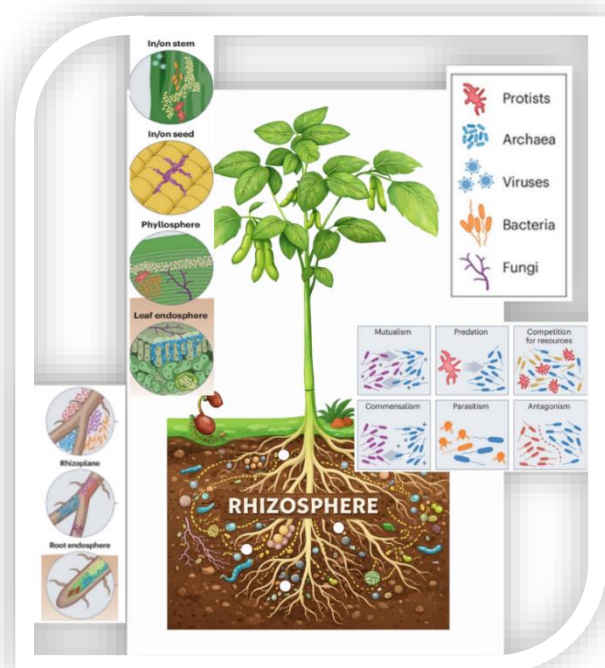
3.2. Applied Microbiome-Based Solutions in Crop Production

3.2.1. Plant Holobiont as a Functional Unit

Modern agricultural systems rely heavily on mineral fertilisers, particularly nitrogen (N) and phosphorus (P), to sustain high crop productivity. However, their use is often inefficient, as a significant proportion of applied nutrients is lost to the environment, contributing to greenhouse gas emissions, water pollution, and soil degradation. At the same time, the production of synthetic fertilisers is energy-intensive and dependent on non-renewable resources.

These limitations highlight the need for alternative approaches that improve nutrient use efficiency while reducing environmental impacts. One of the most important conceptual advances in this context is the recognition of the plant as a **holobiont**—an integrated ecological unit composed of the host plant and its associated microbiome. This concept emphasises that plant performance, health, and adaptation to environmental stress are not determined by the plant alone but emerge from the collective functioning of the plant and its associated microbial communities.

The plant microbiome comprises diverse communities of bacteria, fungi, archaea, viruses, and microscopic eukaryotes inhabiting different plant-associated compartments. These include the **rhizosphere**, the zone of soil directly influenced by plant roots, and the closely associated **rhizoplane**, which represents the root surface and serves as the interface between the plant and the surrounding soil. Microorganisms may also colonise aboveground plant parts, collectively referred to as the **phyllosphere**, including leaves, stems, flowers, fruits, and seeds, forming a continuous and interconnected microbiome across the entire plant (Figure 22).



Microorganisms associated with plants occupy different ecological niches and establish a wide range of interactions with their host, from mutualistic to neutral or even pathogenic. While some microorganisms live inside plant tissues as endophytes, many others remain in the rhizosphere or on root and aboveground surfaces, where they interact closely with plants without entering their tissues (Figure 22). In agricultural systems, particular attention is given to beneficial microorganisms across all these compartments—including free-living, associative, and endophytic species.

Figure 22. Plant holobiont: compartments and interactions of the plant-associated microbiome

3.2.1.1. Soil Microbiome

The soil microbiome represents a major component of the plant holobiont and refers to the highly diverse community of microorganisms inhabiting soil. These organisms interact with each other, with plant roots, and with their surrounding environment, forming complex ecological networks that regulate key ecosystem processes.

Soil microbial communities are extraordinarily diverse; a single gram of soil may contain billions of microbial cells and thousands of microbial taxa. This remarkable diversity underpins the functioning and stability of terrestrial ecosystems and makes soil one of the most biologically active environments on Earth. It has been estimated that a single teaspoon of soil can contain more microorganisms than there are people on the planet. At a larger scale, microbial biomass can also be substantial: within one square meter of soil to a depth of 15 cm, up to 500 g of bacteria, 500 g of actinomycetes, and 1.5 kg of fungi may be present, depending on the ecosystem type (Backer et al., 2018).

Rather than functioning as a uniform system, the soil microbiome performs a wide range of functionally distinct roles that are essential for plant growth, soil fertility, and overall ecosystem sustainability. A simplified overview of the key functional roles of the soil microbiome in agroecosystems is presented in Table 5.

Table 5. Functional roles of the soil microbiome in agroecosystems

Functional role	Key processes	Mechanisms	Relevance for agriculture
Nutrient cycling and availability	Mineralisation, nitrification, denitrification, and biological nitrogen fixation	Enzyme activity, organic acid production, nutrient solubilisation (P, K, S, micronutrients)	Improves nutrient availability and use efficiency; reduces fertiliser inputs
Plant growth promotion and stress tolerance	Phytohormone production (IAA, cytokinins), ACC deaminase activity, osmolyte synthesis	Root stimulation, improved nutrient uptake, stress modulation	Enhances root development, drought tolerance, and crop productivity
Plant health and disease suppression	Competition, antimicrobial production, and induced systemic resistance	Antibiotics, lytic enzymes (chitinases, glucanases)	Reduces disease pressure and dependency on pesticides
Ecosystem functioning and climate regulation	Organic matter decomposition, greenhouse gas regulation	Carbon sequestration, microbial respiration, gas flux control (CO ₂ , N ₂ O, CH ₄)	Supports soil fertility, carbon storage, and climate resilience

Although soil microbial communities are highly diverse, not all microorganisms contribute equally to plant performance. Particular attention is therefore given to functional groups of beneficial microorganisms, such as plant growth-promoting bacteria (PGPB) and mycorrhizal fungi, which play a central role in supporting sustainable crop production. Understanding the functions and interactions of these microorganisms provides a foundation for their targeted use in agricultural systems, where biological processes are increasingly integrated into crop management strategies, including the use of microbial consortia such as effective microorganisms (EM), and microalgae-based solutions.

3.2.2. Biofertilisers and Biostimulants

Building on the understanding of soil microbiome functions, beneficial microorganisms are increasingly used in

agriculture through commercially available products that improve plant productivity, enhance nutrient use efficiency, and increase resilience to environmental stress. These products are designed to support natural plant–microbe interactions and represent practical tools for integrating biological processes into modern crop production systems. Depending on their mode of action and function, these products can be broadly classified into two main groups: **biofertilisers** and **biostimulants**.

Although the term biofertiliser is widely used in scientific literature, it is not formally defined in current European Union legislation. The regulatory framework, established by [Regulation \(EU\) 2019/1009](#) of the European Union, represents an important step towards more sustainable agriculture, as it supports the objectives of the European Green Deal and the Farm to Fork Strategy by promoting the use of biological and low-impact inputs in crop production. Notably, this regulation explicitly recognises microorganisms as components of fertilising products, thereby facilitating the integration of microbiome-based solutions into agricultural practice.

Within this legal context, plant biostimulants (PFC 6) are defined as products that stimulate plant nutrition processes independently of their nutrient content, with the aim of improving nutrient use efficiency, tolerance to abiotic stress, crop quality, or the availability of nutrients in the soil or rhizosphere. This category of plant biostimulants includes both microbial and non-microbial products. Microbial components are currently limited to a small number of authorised groups, including genera such as *Azotobacter*, *Azospirillum*, and *Rhizobium*, as well as arbuscular mycorrhizal fungi. Non-microbial products include substances such as humic and fulvic acids, seaweed extracts, protein hydrolysates, amino acids, plant-derived extracts, and microalgae-based materials.

Position of microbial products in EU fertilising product legislation

- Microbial and non-microbial products are regulated under Regulation (EU) 2019/1009 as **fertilising products**.
- Plant biostimulants are defined as a **Functional Category (PFC 6)**.
- Microorganisms are regulated under **Component Material Category 7 (CMC 7)**, which specifies permitted microbial groups.
- Currently authorised microorganisms include genera such as *Rhizobium*, *Azotobacter*, *Azospirillum*, and arbuscular mycorrhizal fungi.
- Only **living (viable) microorganisms** are included in CMC 7; non-living microbial products (e.g. extracts or metabolites) are regulated under other CMCs and may be used in different product function categories, including plant biostimulants (PFC 6), depending on their intended use
- To obtain **CE marking**, products must meet strict requirements, including:
 - demonstrated agronomic efficacy
 - safety (absence of contaminants)
 - compliance with quality and strain-specific criteria

Future perspectives:

- Harmonised evaluation methodologies are expected by 2026
- Expansion of the authorised microorganism list (CMC 7) is expected from 2027 onwards



3.2.2.1. Biofertilisers (biostimulants according to EU legislation)

Biofertilisers can be classified into several functional groups based on their primary mode of action, including

nitrogen-fixing microorganisms, phosphorus-solubilising microorganisms, potassium- and micronutrient-mobilising microorganisms, mycorrhizal fungi, and microbial consortia. However, not all these groups are equally relevant across agricultural systems. In this module, the focus is placed on biofertilisers most used in European agriculture, particularly in arable crop production:

- A. nitrogen-fixing microorganisms,
- B. arbuscular mycorrhizal fungi (AMF)

A. Nitrogen-fixing microorganisms

Nitrogen-fixing microorganisms play a central role in sustainable crop production by converting atmospheric nitrogen (N_2) into plant-available forms through biological nitrogen fixation (BNF). This process is carried out by specialised prokaryotes (diazotrophs) using the enzyme nitrogenase, which reduces atmospheric nitrogen to ammonia that can be assimilated by plants.

These microorganisms can be broadly divided into two groups:

1. symbiotic nitrogen fixers and
2. free-living or associative nitrogen fixers.

Symbiotic nitrogen fixers (1) are best represented by bacteria of the genera *Rhizobium*, *Bradyrhizobium* (Case study 15), and *Sinorhizobium*, which form highly specific associations with leguminous crops such as soybean, pea, and alfalfa. Following root colonisation, these bacteria induce the formation of root nodules—specialised structures in which nitrogen fixation takes place. Within nodules, atmospheric nitrogen is converted into ammonia, while the plant supplies carbohydrates and maintains a low-oxygen environment required for nitrogenase activity. Well-functioning symbioses can supply substantial amounts of nitrogen and thus significantly reducing the need for synthetic fertilisers and contributing to soil fertility in crop rotations.

In contrast, free-living and associative nitrogen-fixing microorganisms (2) do not form nodules but live independently in the soil or in close association with plant roots. These microorganisms are particularly important for non-leguminous crops such as cereals and vegetables. Although their contribution to nitrogen supply is generally lower than in symbiotic systems, they are widely used due to their additional plant growth-promoting effects. Among them, *Azotobacter* represents a well-known free-living nitrogen fixer that colonises the rhizosphere of a wide range of crops and has long been used as a biofertiliser. *Azospirillum*, on the other hand, forms associative relationships with the roots of grasses (cereals). In addition to contributing to nitrogen availability, it produces phytohormones that stimulate root development, thereby improving nutrient and water uptake.

Azospirillum can be applied as a single microbial inoculant, but it is increasingly used in combination with other beneficial microorganisms, where it acts as a complementary component enhancing plant growth and resource acquisition. Such co-inoculation strategies integrate multiple functional mechanisms and are gaining importance in modern crop production systems. This approach is illustrated in Case Study 15, where *Azospirillum* is used together with symbiotic nitrogen-fixing bacteria in soybean production.

Endophytic nitrogen-fixing bacteria represent a distinct group of diazotrophs that colonise internal plant tissues without forming specialised structures such as nodules. Among them, *Gluconacetobacter diazotrophicus* is one of the most well-studied species. This Gram-negative bacterium, originally isolated from sugarcane, inhabits internal plant compartments such as roots, stems, and vascular tissues, where its close association with the host

enables access to plant-derived carbon sources and facilitates the transfer of biologically fixed nitrogen.

In addition to nitrogen fixation, *G. diazotrophicus* exhibits plant growth-promoting activity through the production of phytohormones such as auxins and gibberellins, which influence root development and overall plant growth. This multifunctional role reflects the dual function of endophytic diazotrophs, which contribute both to plant nutrition (through nitrogen fixation) and to plant growth regulation. It has been detected in a wide range of crops, including rice, maize, coffee, and several horticultural species, highlighting its broader ecological relevance and potential for agricultural application.

However, compared to symbiotic nitrogen fixation systems, its quantitative contribution to plant nitrogen supply remains less well defined and is strongly dependent on plant species, cultivar, and environmental conditions.

Beyond classical endophytic systems, increasing attention is being directed towards plant-associated bacteria that colonise aerial plant parts, particularly the phyllosphere. In this context, species of the genus *Methylobacterium* have emerged as important components of the plant microbiome. These bacteria are metabolically adapted to utilise one-carbon compounds, such as methanol released by plant tissues, and are commonly found on leaf surfaces as well as within plant tissues.

Methylobacterium symbioticum, a recently described species (formally characterised in 2020), represents an example of this group with potential relevance for agricultural systems. It has shown potential across a range of agricultural crops and has been associated with processes such as phytohormone production, modulation of plant metabolism, and improved nutrient use efficiency. Its role in biological nitrogen fixation has been suggested, particularly in aboveground plant compartments, although the mechanisms and extent of its contribution to plant nitrogen nutrition remain under investigation. This microorganism is further examined in Case Study 16, where its performance is analysed based on studies conducted in maize.

B. Arbuscular mycorrhizal fungi (AMF)

Arbuscular mycorrhizal fungi (AMF), belonging to the phylum *Glomeromycota*, form obligate symbiotic associations with the roots of approximately 80% of terrestrial plant species, including most agricultural crops. This symbiosis is based on a bidirectional exchange of resources: plants supply carbon derived from photosynthesis, while the fungi enhance the uptake of mineral nutrients and water from the soil.

The establishment of this interaction involves the formation of a functional mycorrhizal network consisting of structures within the root and hyphae extending into the surrounding soil. The extraradical mycelium increases the volume of soil explored and enables access to poorly mobile nutrients, while within root cortical cells, AMF form arbuscules—highly branched structures that represent the primary site of nutrient exchange between the fungus and the host plant. In addition, some AMF form vesicles, which serve as storage structures and contribute to the persistence of the symbiosis.

Functionally, AMF contribute to plant nutrition by improving the uptake of both macro- and micronutrients, particularly phosphorus, but also nitrogen from both inorganic and organic sources (e.g. amino acids), sulphur, potassium, and trace elements. Beyond nutrient acquisition, they play an important role in soil functioning: their hyphal networks and associated compounds (e.g. glomalin) enhance soil aggregation, improve soil structure, and increase water retention, thereby supporting soil fertility and resilience. AMF also influence plant responses to environmental stress by improving water uptake, modulating plant physiology, and activating defence mechanisms. As a result, they can enhance tolerance to drought, salinity, and heavy metal stress, and contribute to protection against soil-borne pathogens.

At the agroecosystem level, AMF are key contributors to nutrient cycling, soil formation, and carbon dynamics. However, their effectiveness in agricultural systems as biofertilisers is highly context-dependent and influenced by soil properties, management practices, plant–fungus compatibility, and interactions with native microbial communities. This complexity is further explored in Case Study 17.

3.2.2.2. Microbial Consortia (e.g. Effective Microorganisms, EM)

In practical applications, commercial microbial products are commonly based on single strains of selected microorganisms, although multi-strain formulations are becoming increasingly available. These microbial consortia combine organisms with complementary functions, such as nutrient mobilisation, plant growth promotion, and stress tolerance.

One of the most widely known examples of this approach is the concept of Effective Microorganisms (EM), originally developed by Professor Teruo Higa in the 1980s. The concept is based on the idea that introducing selected groups of beneficial microorganisms into the environment can shift microbial communities towards more favourable, regenerative processes. EM formulations typically include mixtures of lactic acid bacteria, photosynthetic bacteria, yeasts, and other microorganisms.

Environmental applications of EM have been more consistently reported than their use in crop production. According to current literature, EM have been applied in composting systems, where they can accelerate the decomposition of organic residues and improve compost quality. They have also been used in wastewater treatment and sludge management, where they may contribute to the reduction of organic pollutants, odours, and pathogen loads. Additional applications include waste stabilisation, bioremediation of contaminated soils, and improvement of environmental hygiene in livestock systems. In these contexts, where organic substrates are abundant and microbial processes are strongly substrate-driven, EM can support enhanced microbial activity and transformation processes.

In contrast, their effectiveness in crop production systems is less consistent. In agricultural soils, where microbial communities are already highly diverse and competitive, introduced microorganisms must interact with established native populations. As a result, the performance of EM products in terms of plant growth and yield is variable and strongly dependent on environmental conditions, soil properties, and management practices. Some observed positive effects may also be linked to organic components in the formulations rather than to microbial activity alone.

3.2.3. Formulation of Biofertilisers and Biostimulants

Formulation plays a critical role in determining the effectiveness of biofertilisers and biostimulants. It involves combining active biological components with carriers and additives that ensure stability, viability, and ease of application. Different formulation strategies influence product shelf life, application methods, and field performance. The main formulation types and their characteristics are illustrated in Figure 23 and summarised in Table 6.

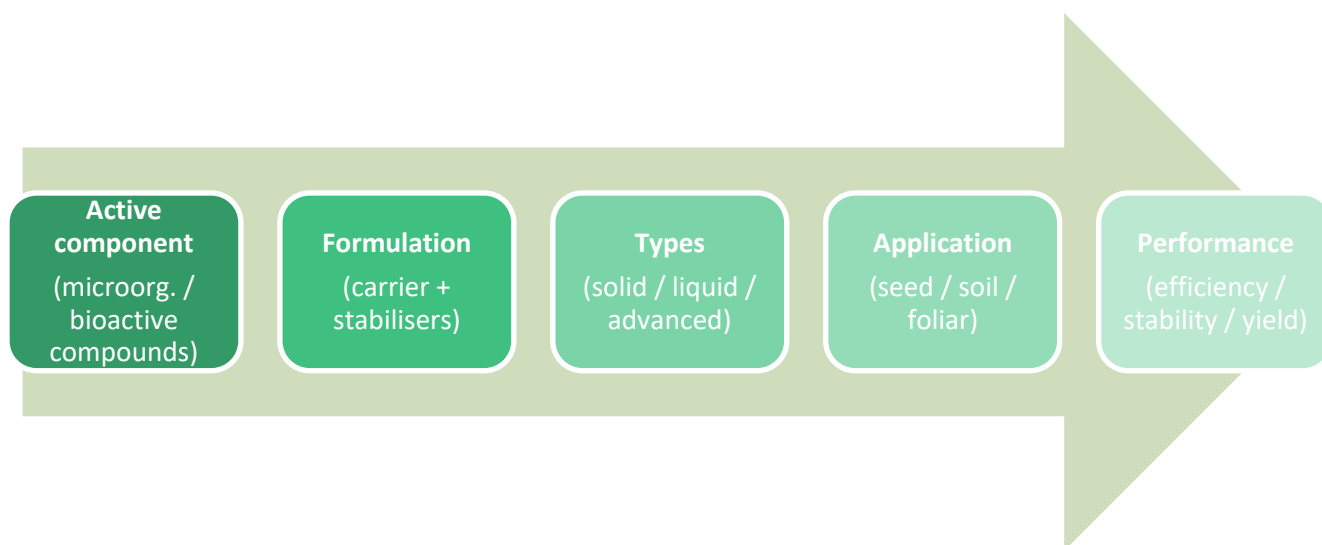


Figure 23. Conceptual overview of biofertiliser and biostimulant formulation, from active components to field performance

Table 6. Overview of formulation types used in biofertilisers and biostimulants

Formulation type	Description	Advantages	Limitations	Typical applications
Solid formulations (powders, granules, microgranules)	Microorganisms or bioactive compounds bound to solid carriers	Easy storage and transport; high stability; cost-effective	Lower microbial density; slower activation in soil	Soil application, seed coating
Liquid formulations	Suspensions of microorganisms or dissolved compounds in water or oil	Easy application; compatible with irrigation systems; high cell density	Sensitivity to storage conditions; risk of microbial decline	Seed treatment, fertigation
Encapsulated formulations	Microorganisms enclosed in protective matrices (e.g. polymer beads)	Protection from environmental stress; controlled release	Higher cost; possible oxygen limitation	Targeted soil application
Emulsions	Mixtures of immiscible liquids (oil/water) stabilised by surfactants	Improved stability; controlled release; scalable	Requires careful formulation stability control	Foliar application, liquid products
Dry formulations (e.g. fluidised bed drying)	Removal of moisture to stabilise microbial products	Extended shelf life; reduced contamination	Processing complexity	Commercial inoculants
Nano-formulations	Active compounds or microorganisms at nanoscale	Improved delivery efficiency; reduced losses	Still under development; regulatory uncertainty	Emerging technologies

Case study 15: Biological Nitrogen Fixation as a Foundation of Soybean Production Systems (Telles et al., 2023: <https://doi.org/10.1016/j.eti.2023.103158>)



Figure 24. Soybean root nodules

Overview: Soybean (*Glycine max* L.) is one of the most important global crops, and Brazil is among the world's leading producers and exporters, supplying a substantial share of soybeans used in international markets, including the European Union. This makes Brazilian soybean production systems highly relevant for understanding the role of microbial processes in large-scale agriculture.

Challenge: Nitrogen is a key limiting nutrient in crop production and is typically supplied through synthetic fertilisers. However, nitrogen fertilisation is associated with high economic costs, low use efficiency, and significant environmental impacts. The central challenge is whether biological processes can reliably replace mineral nitrogen inputs under intensive production conditions.

Biotech Approach and Solution: soybean production systems in Brazil rely on inoculation with selected strains of *Bradyrhizobium* spp., which form highly efficient symbioses with soybean and enable biological nitrogen fixation (BNF) at a scale sufficient to meet crop nitrogen demand. These strains have been specifically selected and optimised over decades for local soil and climate conditions, as well as for compatibility with soybean cultivars. Importantly, although soils often contain native rhizobial populations, annual reinoculation remains standard practice, as introduced elite strains typically ensure more effective nodulation and nitrogen fixation. In addition, co-inoculation with *Azospirillum brasilense* is increasingly adopted to complement symbiotic nitrogen fixation with plant growth-promoting effects, particularly through improved root development and resource acquisition.

In Brazilian soybean production systems, nitrogen fertilisers such as urea are generally not applied. Instead, crop nitrogen demand is met primarily through biological nitrogen fixation. In this study, the value of BNF was estimated by calculating how much mineral nitrogen fertiliser would be required in its absence, assuming a fertiliser nitrogen use efficiency of 50%.

Field-Scale Evidence: Brazilian soybean systems demonstrate the large-scale impact of BNF

- Replacement of mineral nitrogen fertilisers generated approximately 15.2 billion USD in savings per growing season.
- Co-inoculation technology has been rapidly adopted, reaching approximately 25% of the soybean production area (~10 million ha). This rapid adoption is linked to its agronomic benefits, as co-inoculation with *Bradyrhizobium* and *Azospirillum brasilense* has been shown to result in higher yield increases compared to single inoculation, reflecting the advantages of combining complementary microbial functions.
- Avoided greenhouse gas emissions reached approximately 183 million Mg CO₂-equivalent.

The importance of biological nitrogen fixation extends beyond agronomic and economic benefits. In Brazil, BNF is recognised as a key mitigation strategy within national climate policies, including the Low Carbon Agriculture Plan (Plano ABC, 2010–2020) and its continuation Plano ABC+ (2021–2030). This highlights the role of microbial processes as measurable and auditable contributions to greenhouse gas mitigation in agriculture.

Case Study 15: Critical Reflection for Students

- Why is reinoculation recommended even in soils where compatible rhizobia are already present?
- Are microbial inoculants based on *Bradyrhizobium* and *Azospirillum* available on the national or EU market? Under which commercial names are these products marketed, and in which formulations are they available (e.g. liquid inoculants, seed coatings, granules)?
- How do manufacturers communicate product efficacy and expected benefits? Which claims are supported by scientific evidence, and which may rely primarily on marketing?
- How could the effectiveness of such products be independently evaluated under field conditions? What experimental design would you propose?

Additional Quantitative Exercise

Using available data on biological nitrogen fixation (e.g. $\sim 100 \text{ kg N ha}^{-1} \text{ year}^{-1}$ reported for Slovenia), estimate the agronomic and economic value of BNF.

1. If biological nitrogen fixation supplies 100 kg N ha^{-1} , how much mineral nitrogen fertiliser (urea, CAN) would be required to provide the same amount of plant-available nitrogen, assuming a nitrogen use efficiency (NUE) of 50%?
2. Based on current fertiliser prices, estimate the cost per hectare and the total cost for a selected (average) farm size
3. How realistic is it to assume a constant nitrogen use efficiency (50%) across different soils and climatic conditions? Which factors could influence this value in practice?

Write your notes:

Case study 16: Foliar Application of *Methylobacterium symbioticum* in Maize – Potential and Variability of Responses

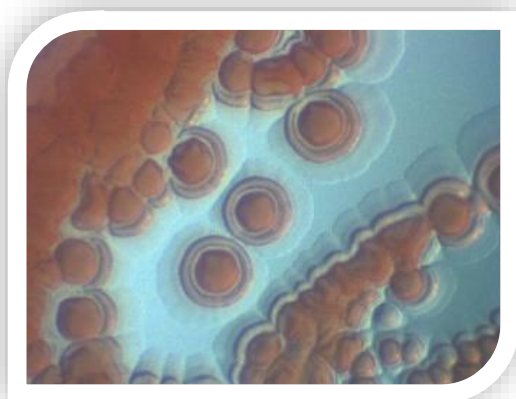


Figure 25. Microscopic view of a colony of *M. symbioticum* Source: Symborg (2025)

Overview: Recent developments in microbial products for crop production include foliar-applied bacteria such as *Methylobacterium symbioticum*, which are proposed to enhance plant growth and contribute to nitrogen nutrition in non-leguminous crops. Unlike root-associated systems, these microorganisms colonise the phyllosphere and are applied directly to leaves.

Challenge 1: Maize has a high nitrogen demand, and nitrogen is often applied in split doses to improve efficiency and reduce losses. However, later applications can be technically challenging, as increasing plant height limits field access. While solutions such as liquid fertilisers and aerial

applications exist, they are not always practical or cost-effective.

Biotech Solution / Opportunity: Several studies have reported positive effects of *M. symbioticum* on maize performance. Under certain conditions, inoculated plants showed:

- increased nitrogen content in plant tissues (Quemada et al., 2026),
- improved biomass production and root development (Bolla et al., 2025).
- higher grain yield, particularly in non-fertilised treatments (e.g., increases from ~5.1 to 7.3 t ha⁻¹)
- the potential to partially replace mineral nitrogen inputs (Quemada et al., 2026),

Challenge 2: Inconsistent evidence: despite promising results, the agronomic effectiveness of *M. symbioticum* remains highly variable.

- In several field experiments, yield increases were observed but were not always statistically significant (Bolla et al., 2025).
- Under optimal nitrogen fertilisation, the effect of inoculation often disappeared (Quemada et al., 2026).
- Responses varied across locations and environmental conditions (de Jesus Santos & Da Cas Bundt, 2025).

The mechanism of action is still debated, as clear evidence for atmospheric nitrogen fixation is lacking in some studies. Observed effects may be related to plant growth promotion (e.g. root development, hormone production) rather than direct nitrogen fixation.

Interpretation: This case illustrates the complexity of translating microbial potential into consistent agronomic performance. While *M. symbioticum* demonstrates clear potential under specific conditions—particularly when nitrogen availability is limited—its effectiveness cannot be generalised across all production systems.

Case study 16: Critical Reflection for Students

- How do results differ between controlled experiments (pots, greenhouse) and field trials?
- Why is this microorganism particularly interesting for agricultural use? Consider the plant species and tissues it colonises, as well as its possible modes of action.
- How do manufacturers communicate product efficacy and expected benefits? Which claims are supported by scientific evidence, and which may rely primarily on marketing?

Write your reflection below:

Case study 17: Arbuscular Mycorrhizal Fungi – High Potential with Context-Dependent Effectiveness as Biofertilisers (Berruti et al., 2016: <https://doi.org/10.3389/fmicb.2015.01559>)

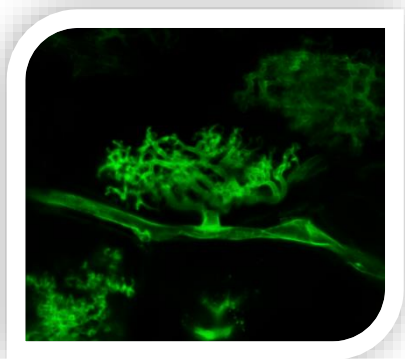


Figure 26. Arbuscule of *Rhizophagus irregularis* colonising a maize root, observed under a confocal microscope, Source: Montero (2019)

Overview: arbuscular mycorrhizal fungi (AMF) are widely recognised for their ecological importance and their potential role in sustainable agriculture. However, despite their well-established functions, their application as biofertilisers in agricultural systems remains limited and often produces inconsistent results.

Challenge 1: phosphorus is an essential nutrient for plant growth, but its availability in soil is often limited due to low mobility and strong fixation to soil particles. As a result, crops frequently cannot access sufficient phosphorus, even when fertilisers are applied. Improving phosphorus use efficiency remains a key challenge in sustainable crop production.

Biotech Solution / Opportunity

AMF are expected to contribute to plant nutrition and soil functioning, particularly in systems where nutrient availability is limited. Their role in supporting phosphorus acquisition and improving plant performance makes them attractive for reducing dependence on mineral fertilisers.

Challenge: Despite their high potential, several biological and technological constraints limit the broader practical use of AMF as biofertilisers. A key limitation is that AMF are obligate symbionts, meaning they cannot be cultured independently of a host plant. As a result, inoculum production requires plant-based systems, which are more complex and less scalable than microbial fermentation used for bacterial inoculants. In addition, the response to AMF inoculation is often variable under field conditions. Agricultural soils typically already contain native AMF communities, and introduced strains must compete with these established populations. Consequently, inoculation does not always lead to measurable agronomic benefits. The effectiveness of AMF is further influenced by soil nutrient status, particularly phosphorus availability, agricultural management practices, plant–fungus compatibility and environmental conditions.

Technology and Application: AMF inoculants are produced using host plants in controlled systems and are typically formulated as solid carriers containing spores, hyphae, and colonised root fragments. Compared to bacterial inoculants, AMF products are more difficult to standardise, and their performance is less predictable across different agroecosystems.

Interpretation: This case highlights the difference between biological potential and agronomic applicability. While AMF plays a fundamental role in ecosystem functioning, their effectiveness as applied biofertilisers is not universal.

Case study 17: Critical Reflection for Students

- Are microbial inoculants based on AMF available on the national or EU market? Under which commercial names are these products marketed, and in which formulations are they available?
- How do manufacturers communicate product efficacy and expected benefits? Which claims are supported by scientific evidence, and which may rely primarily on marketing?
- How could the effectiveness of such products be independently evaluated under controlled (pot) and field conditions? Would you expect similar results? Why or why not? Which factors could explain potential differences?

Write your reflection below:

3.2.4. GIS Analysis of Environmental Factors Influencing the Soil Microbiome in the Context of Climate Change

3.2.4.1. Environmental factors influencing soil microbiome

The composition and functioning of the soil microbiome are strongly shaped by environmental factors, which vary across landscapes and determine the physical and chemical environment in which microorganisms live. Among many factors, soil microbial communities respond to soil properties, climate, vegetation, and land use. Understanding these environmental factors is essential for interpreting the distribution and functioning of soil microbial communities and for linking microbiological processes with broader spatial systems.

Among soil characteristics, soil pH is consistently identified as one of the strongest predictors of microbial diversity at regional and global scales. Studies have shown that bacterial community composition changes with soil pH, with different microbial taxa adapted to acidic, neutral, or alkaline conditions. In general, bacterial diversity in soils is typically highest near neutral pH (approximately pH 6–7.5), whereas strongly acidic or alkaline soils often support lower diversity and distinct microbial communities. Other important soil properties include soil organic carbon, nutrient availability, soil texture, and soil moisture.

Climate strongly influences soil microbial processes by controlling temperature and water availability. Microbial metabolic rates generally increase with temperature within biologically tolerable ranges, accelerating organic matter decomposition and nutrient mineralization. Water availability is equally important because most soil microorganisms require thin water films in soil pores for movement and biochemical reactions. As soils become drier, microbial activity and decomposition rates typically decline. Because climate change is expected to increase drought frequency and aridity in many regions, these shifts in microbial activity may alter soil carbon cycling, nutrient availability, and long-term soil fertility.

Another major driver of soil microbial communities is vegetation and land use. Different plant species influence microbial communities through roots, litter inputs, and symbiotic relationships with soil organisms. As a result, forests, grasslands, and other natural ecosystems systems often support larger and more diverse microbial communities. Land-use practices such as cultivation, fertilization, irrigation, and grazing can modify soil conditions and microbial processes. In addition to these factors, topography influences soil microbial environments by shaping local conditions such as soil moisture, erosion processes, and nutrient redistribution. Variables such as elevation, slope, and landscape position affect drainage patterns and microclimatic conditions, which in turn influence microbial activity and community structure.

Together, these environmental variables form complex spatial gradients that structure soil microbial communities across landscapes. Because many of these factors—such as climate variables, land cover, vegetation productivity, and topography—can be represented as spatial datasets, they provide a foundation for analysing soil microbiomes using geographic information systems (GIS).

3.2.4.2. GIS and Digital Integration for Analysing and Managing Soil Microbiomes

The environmental factors that influence the soil microbiome vary across space, creating distinct spatial patterns in soil conditions and microbial communities. Geographic Information Systems (GIS) provide a framework for analysing these patterns by integrating spatial datasets describing climate, soil properties, vegetation, and topography. By combining environmental data with field observations, GIS enables the investigation of how

environmental conditions shape soil microbial processes at landscape and regional scales.

Many environmental variables known to influence soil microbiomes are available as spatial datasets. Climate variables such as temperature and precipitation can be obtained from global and regional climate databases (e.g. WorldClim), while soil properties such as pH, organic carbon, texture, and nutrient availability (e.g. N and P) are available through global soil mapping initiatives such as SoilGrids or the European Soil Data Centre.

Remote sensing products derived from satellite imagery provide information on vegetation productivity and land cover, including indicators such as the Normalised Difference Vegetation Index (NDVI), which is widely used to estimate vegetation activity and biomass. In addition, topographic variables such as elevation, slope, and aspect can be derived from digital elevation models and influence soil moisture distribution, erosion processes, and local microclimatic conditions.

A useful GIS approach for combining multiple environmental variables is weighted overlay analysis, a method commonly used in spatial decision-support and environmental suitability assessments. In this approach, environmental variables are first transformed into comparable scales that represent their suitability or influence on a given process. Each factor is then assigned a weight reflecting its relative importance, and the weighted layers are combined to produce a composite map that represents the spatial distribution of favourable environmental conditions.

When applied to soil microbiome studies, weighted overlay analysis can integrate variables such as soil pH, temperature, precipitation, vegetation productivity (e.g. NDVI), soil moisture, and nutrient availability to identify areas where environmental conditions are likely to support specific microbial processes or higher microbial activity. For example, soils with near-neutral pH, moderate temperatures, sufficient moisture, and balanced nutrient availability may provide favourable conditions for microbial decomposition and nutrient cycling.

Recent developments extend beyond static spatial analysis by incorporating real-time environmental data and biological information. Sensor technologies (e.g. soil moisture, temperature, and nutrient sensors), remote sensing (e.g. UAV-based monitoring), and digital platforms enable continuous observation of soil and crop conditions. At the same time, advances in microbiome analysis, including metagenomics and functional profiling, provide insights into the composition and functional potential of microbial communities.

The integration of these data sources within GIS-based frameworks allows for a more comprehensive understanding of plant–soil–microbe interactions under variable field conditions. This approach supports the delineation of management zones and enables more targeted and context-specific agricultural practices (Case study 18).

Such integration is increasingly reflected in the development of Smart-MIP (Microbial- and Sensor-Based Integrated Precision) systems. These systems combine microbial products, sensor technologies, spatial analysis, and data-driven tools into a unified framework for decision-making. By linking biological processes with spatial and temporal data, Smart-MIP systems aim to optimise the placement, timing, and effectiveness of microbial applications in agriculture (Figure 24).

Case study 18: From Microbial Products to Precision Microbiome Management – Integrating Soil Microbiome, Sensors and GIS (Ambaru et. al., 2025: <https://doi.org/10.1016/j.eti.2023.103158>; Danesh, 2025: <https://doi.org/10.3390/s25216631>)

Overview: The effectiveness of microbial products in crop production is often inconsistent, as their performance depends on environmental conditions, soil properties, and spatial variability within fields. At the same time, advances in digital agriculture are enabling a better understanding and management of this variability.

Challenges:

1 – Spatial variability of soil and microbial processes

Soil properties such as pH, moisture, organic matter, and nutrient availability vary across fields and strongly influence microbial activity. As a result, responses to microbial products are uneven, ranging from strong positive effects to little or no response.

2 – Limited ability to predict where microbial products will be effective

Although microbial products have significant potential, their performance is difficult to predict under field conditions. Traditional management approaches often lack spatially explicit information linking soil conditions, crop status, and microbial activity.

Biotech Solution / Opportunity

A new generation of approaches combines:

- microbial products (biofertilisers, biostimulants)
- soil microbiome analysis (metagenomics, functional profiling)
- sensor technologies (soil moisture, temperature, nutrient status)
- remote sensing (UAV, vegetation indices such as NDVI)
- GIS-based spatial analysis

These technologies enable the identification of spatial variability, mapping of conditions influencing microbial activity, and integration of biological and environmental data. GIS serves as a central platform to define management zones where microbial products can be applied more effectively. This integration forms the basis of **Smart-MIP (Microbial- and Sensor-Based Integrated Precision) systems**, which support targeted and adaptive crop management.

Example scenario

A maize field shows strong spatial variability:

- upper slopes are drought-prone with lower organic matter
- lower areas are wetter, with a risk of waterlogging

Using soil data (pH, organic matter, nutrient availability), sensor measurements (soil moisture), and remote sensing indicators (NDVI), the field is divided into management zones.

A microbial product (e.g. *Azospirillum* or *Methylobacterium symbioticum*) is then applied selectively:

- in stress-prone zones where plant performance is limited
- in areas where soil conditions support beneficial plant–microbe interactions
- using soil or foliar application at appropriate growth stages

In other zones, application may be reduced or omitted.

Case study 18: Critical Reflection for Students

- Why does the effectiveness of microbial products vary across different parts of the same field? Which soil and environmental factors are most important?
- How can spatial data (e.g. soil properties, NDVI, moisture) help explain differences in crop response to microbial products?
- What are the advantages of applying microbial products site-specifically rather than uniformly?
- Which technologies are combined in Smart-MIP systems, and how do they improve decision-making in crop production?
- In the example scenario, how would you define management zones and decide where microbial application is most appropriate?
- What are the main limitations or challenges of implementing such approaches in practice (e.g. cost, data availability, knowledge)?

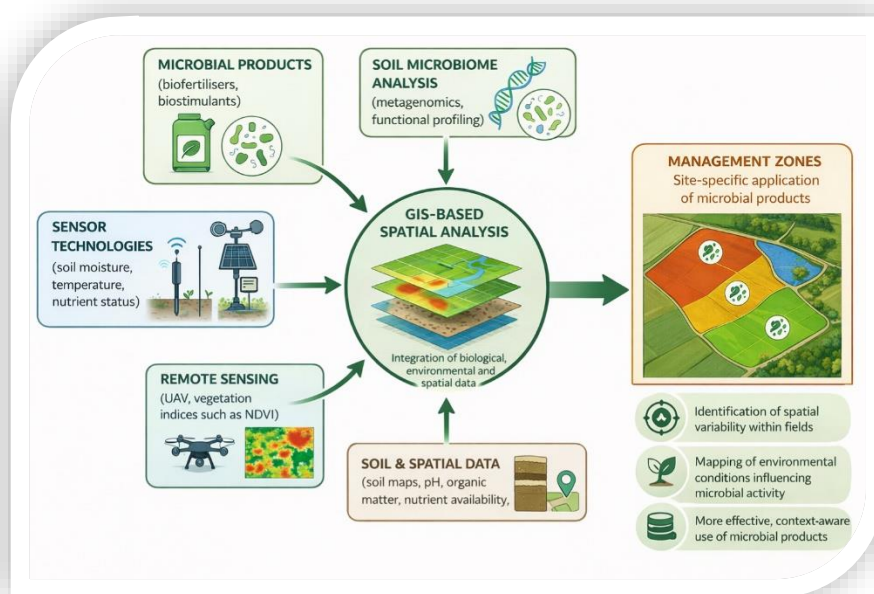


Figure 27. From data to decision: site-specific application of microbial products

Write your reflection below:

3.2.5. Integrating Microbiome-Based Solutions into Climate-Smart Agriculture

The soil microbiome is increasingly recognised as a key component of climate-smart agriculture. Throughout this chapter, it has been shown that microorganisms contribute to nutrient cycling, plant nutrition, stress tolerance, soil functioning, and the overall resilience of agroecosystems. Their importance is reflected not only in natural plant–soil interactions, but also in the growing development of microbial products such as biofertilisers, biostimulants, and microbial consortia.

At the same time, the chapter also highlights that microbiome-based solutions cannot be understood or applied in isolation. Their effects depend on the interaction between microorganisms, plants, soil conditions, and management practices, and these interactions are further shaped by spatial and temporal variability across fields and landscapes. For this reason, the future of microbiome-based agriculture is likely to depend increasingly on integrative approaches that combine biological knowledge with spatial analysis, real-time monitoring, and digital decision support.

In this context, GIS, sensor technologies, remote sensing, IoT-based monitoring, artificial intelligence, and precision farming tools create new opportunities for linking microbial processes with field conditions more effectively. Together with advances in microbiome analysis and targeted microbial formulations, these technologies support the transition from uniform input use towards more site-specific and data-informed crop management.

Overall, the most promising role of microbiome-based solutions in agriculture lies not in replacing all conventional inputs, but in contributing to more efficient, adaptive, and sustainable production systems. Integrated approaches such as Smart-MIP illustrate this direction by combining microbial products, environmental data, and digital tools into a more coordinated framework for climate-smart crop production.

My notes:

3.3. Innovation Work Areas for Students

Use this template to plan and document your experiment, including the selection of plant material, microbial product, stress conditions, experimental design, and measurements.

BIOSHIELD STUDENT PROJECT

TRANSFERRING INNOVATION INTO PRACTICE

Evaluating the Performance of Microbial Products under Climate Stress

Students will design and conduct a small-scale experiment to evaluate the performance of a commercial microbial product in crop systems under specific environmental stress conditions (e.g. drought or waterlogging), reflecting challenges associated with climate change in agriculture.

STEP 1: DEFINE THE SYSTEM

- Laboratory, growth chamber, greenhouse, pot or field experiment?
- Select a plant species and appropriate cultivar(s) (preferably with a short growth cycle)
- Choose one or more commercial microbial products available on the local market
- Define the plant growth stage(s) to be evaluated (e.g., germination, early vegetative growth, or a defined growth period)

STEP 2: DEFINE THE PROBLEM

- Identify a climate-related stress factor (e.g., drought, waterlogging)
- Define the research question
- Clarify the expected effect of the stress on plant performance

STEP 3: DEFINE EXPERIMENTAL FACTORS

- Select the main experimental factors
- Define levels for each factor (e.g., dose, application method, stress intensity)
- Define treatments, including appropriate controls
- Calculate the total number of experimental units / no. of plants

STEP 4: DEFINE RESEARCH QUESTION(S) AND FORMULATE HYPOTHESES

- Formulate clear and testable hypotheses based on the research question(s)

STEP 5: DESIGN AND ESTABLISH THE EXPERIMENT

- Define the experimental layout and number of replicates
- Specify when and for how long the stress will be applied
- Describe how the stress will be maintained and monitored
- Define what will be measured, how, and when (measurement plan)
- Prepare a Materials & Methods plan
- Review the Materials & Methods with peers (from another group), a supervisor, or an expert, and revise if needed

STEP 6: CONDUCT THE EXPERIMENT

- Apply treatments and maintain experimental conditions
- Carry out measurements according to the plan
- Record observations and data systematically

STEP 7: ANALYSE OBTAINED DATA

- Calculate relevant parameters or indices (e.g. biomass increase, root:shoot ratio, stress response indicators)
- Perform basic statistical analysis (if applicable)
- Organise results (tables, graphs, images)
- Interpret findings in relation to the research question and hypotheses

STEP 8: COMMUNICATE THE FINDINGS

- Prepare a written report, poster, or presentation
- Present and discuss results with peers
- Reflect on limitations and possible improvements
- Adapt communication to different audiences (scientific vs. practical/agronomic)

Start by defining your experimental system and conditions carefully. A well-designed experiment is essential for obtaining meaningful results.



Figure 28. Inquiry about definitions

Plant system: Species and cultivar(s); justification of choice

Microbial product(s): Commercial name, microbial strain(s), formulation, recommended dose, application method and timing (according to manufacturer)

Climate stress factor: Type of stress *e.g. drought, waterlogging*, stress timing (*at which growth stage(s) / days after sowing / emergence, stress duration ...*)

Native soil/substrate characteristics: *e.g. site of soil collection, substrate/soil physical and chemical properties*

....

Experimental factors: Which factors will be tested (e.g. dose, application method, stress) and **levels for each factor** (e.g. 0, recommended, increased dose), non-sterile or autoclaved soil/substrate as control(s) treatment? no. of treatments and replications per treatment, experimental units as pots, trays, plots, no. of plants per unit, unit coding (to avoid bias) ...

Data recording method: Notebook, spreadsheet, tablet, app

Timeline: Key steps (sowing, application, stress, measurements, harvest)

Review notes: Feedback from peers, supervisor, or expert

Select only those measurements that help you answer your research question. Define in advance what, how, and when you will measure, and ensure consistency across all treatments. Record data systematically and plan how results will be analysed and presented.

The measurements and analyses listed below are examples of commonly used parameters and basic approaches; they should be adapted to your specific experimental design and research objectives.

Figure 29. Inquiry about measurement and analysis of results



Table 7. Measurement and analysis of results

Measurements			
What?	Why?	Method/device	When?
Germination and other BBCH development stages	(Early) plant response	Counting, estimating	Regarding development (in days after sowing)
Plant height	Growth indicator	Ruler	At defined intervals
Leaf number	Development stage	Counting	At defined intervals
Root length	Root development	Image analysis	Final harvest
Fresh biomass	Growth response	Weighing	Harvest
Dry biomass (yield to certain moisture)	Stable biomass measure	Drying + weighing	Harvest
Visual stress symptoms	Stress response	Scoring scale/photos	During stress period
Chlorophyll (SPAD)	Physiological status	SPAD meter,	Defined intervals
Photosynthesis measurement (+ soil respiration)		Portable Photosynth. Systems	
Soil moisture	Stress monitoring	Sensor, gravimetric method	Regular intervals
Calculations, analyses			
Calculated parameters, indices	e.g. biomass increase, root, shoot ratio, stress tolerance index		
Data organisation	Tables, spreadsheets (e.g. Excel)		
Statistical software	e.g. SPSS, SAS, R, Excel, Jamovi		
Statistical method	e.g. homogeneity, normality tests, t-test, ANOVA, multiple range tests		
Graphical representation	Bar chart, line graph, boxplot		
Key results	Main findings,		
Interpretation	What do the results mean?		

3.4. Conclusion

This chapter explains how the soil microbiome can support climate-smart crop production and sustainable landscape management. Agriculture is under increasing pressure from population growth, hunger, limited arable

land, soil degradation, urbanization, and climate change. Modern farming also depends strongly on synthetic fertilizers, although crops use only part of the applied nutrients. The rest may be lost to the environment, causing greenhouse gas emissions, water pollution, eutrophication, and further soil degradation.

Microbiome-based solutions are presented as one response to these problems. They include biofertilisers, biostimulants, and microbial consortia, which support natural plant–microbe interactions. The chapter uses the concept of the plant holobiont, where the plant and its associated microorganisms function together. These microorganisms occur in the soil, rhizosphere, root surface, internal plant tissues, and aboveground plant parts, where they influence plant nutrition, growth, health, and stress tolerance.

The soil microbiome has essential functions in agroecosystems. Soil microorganisms contribute to nutrient cycling, organic matter decomposition, biological nitrogen fixation, phosphorus mobilization, disease suppression, soil structure formation, carbon storage, and greenhouse gas regulation. Beneficial groups, especially plant growth-promoting bacteria and arbuscular mycorrhizal fungi, can improve nutrient availability, root development, water uptake, soil fertility, and crop resilience.

The chapter presents several applied microbial solutions. Nitrogen-fixing microorganisms convert atmospheric nitrogen into plant-available forms. Symbiotic bacteria such as *Rhizobium* and *Bradyrhizobium* are important for legumes, while *Azotobacter*, *Azospirillum*, endophytic bacteria, and leaf-associated bacteria may support other crops. Arbuscular mycorrhizal fungi improve phosphorus and nutrient uptake, support soil aggregation, and can increase tolerance to drought, salinity, heavy metals, and some soil-borne pathogens. Microbial consortia, including Effective Microorganisms, combine several microbial groups and are used in composting, wastewater treatment, sludge management, bioremediation, livestock systems, and crop production. However, microbial products are not universal solutions. Their effectiveness depends on microbial strain, crop species, soil properties, climate, nutrient availability, native microbial communities, formulation, storage, and application method. Different formulations, including solid, liquid, encapsulated, dry, emulsion, and nano-formulations, influence product stability, shelf life, application, and field performance. Therefore, product claims should be evaluated critically through controlled experiments, field testing, and clear measurements.

The chapter also links soil microbiomes with GIS and digital integration. Soil microbial communities are shaped by spatially variable factors such as soil pH, moisture, temperature, organic carbon, nutrients, vegetation, land use, and topography. GIS can combine climate data, soil maps, satellite imagery, NDVI, land cover data, and digital elevation models to identify favorable environmental conditions for microbial activity or plant–microbe interactions. Weighted overlay analysis and Smart- MIP systems support more targeted microbial applications by combining microbial products, soil microbiome analysis, sensors, remote sensing, GIS, and data-driven tools.

Overall, the chapter shows that soil microbiomes have strong potential in climate-smart agriculture, but their successful use requires biological knowledge, spatial analysis, experimental testing, and critical evaluation.

Chapter 4 - Biotechnology for Carbon Capture and Utilisation

4.1. Introduction: The Strategic Integration of Biosciences in Climate Mitigation

The trajectory of the 21st century is defined by the urgent necessity to rebalance the global carbon cycle. The cumulative accumulation of anthropogenic greenhouse gases (GHGs) has precipitated a climate emergency that demands a multifaceted response, transcending the traditional dichotomy of emissions reduction versus adaptation. While the decarbonization of energy and transport sectors remains the primary imperative, the Intergovernmental Panel on Climate Change (IPCC) has rigorously established that these measures alone are insufficient to limit global warming to 1.5°C or even 2°C above pre-industrial levels (Masson-Delmotte et al., 2018). To meet the targets set by the Paris Agreement, humanity must actively remove gigatons of carbon dioxide (CO₂) from the atmosphere—a process known as Carbon Dioxide Removal (CDR) or "negative emissions".

Historically, the discourse on carbon capture has been dominated by geological and engineering solutions, such as Direct Air Capture (DAC) and Point-Source Carbon Capture and Storage (CCS). These technologies, while essential, often view carbon as a waste product to be buried in subterranean reservoirs.³ However, a parallel and increasingly sophisticated paradigm is emerging: Biotechnology for Carbon Capture and Utilisation (Bio-CCU). This approach reframes carbon not as a waste product, but as a fundamental biological feedstock—the essential building block of life, materials, and energy.

This chapter serves as a comprehensive educational resource for the Erasmus+ project "Novel Biotechnological Solutions in Climate Change Mitigation." Designed for students and educators, it bridges the gap between fundamental biological principles and cutting-edge climate applications. It explores how biological systems—ranging from the deep roots of genetically optimised crops to the metabolic pathways of microscopic cyanobacteria—can be harnessed to sequester atmospheric carbon and convert it into stable, economically valuable forms.

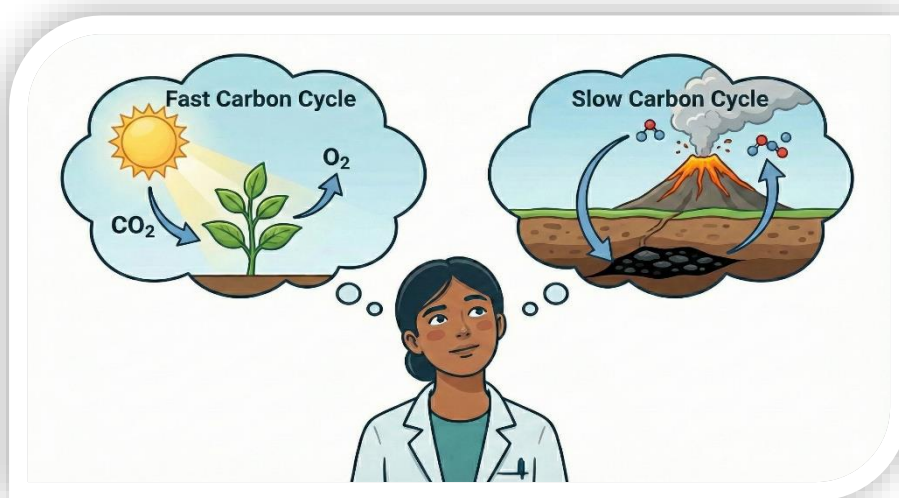


Figure 30. Primary domains of the carbon cycle

To understand the potential of biotechnology, one must first distinguish between the two primary domains of the carbon cycle:

1. **The Slow Carbon Cycle:**

This cycle operates on geological timescales (millions of years). Carbon flows between rocks, soil, ocean, and atmosphere through volcanic eruptions, chemical weathering, and sediment formation. Fossil fuels represent a reservoir of "slow" carbon that has been sequestered for hundreds of millions of years. Burning them releases this carbon into the atmosphere almost instantaneously, overwhelming the system.

2. **The Fast Carbon Cycle:**

This cycle operates on biological timescales (years to decades). Carbon moves between the biosphere and atmosphere through photosynthesis and respiration. Plants absorb CO₂ to build biomass; when they die or respire, that carbon is released back into the air.

3. **The Biotechnological Challenge:**

Standard biological processes are carbon-neutral over the short term; a tree grows (absorbing carbon) and eventually rots (releasing carbon). The objective of Bio-CCU is to intervene in the fast cycle to increase the residence time of carbon in the biosphere or to transfer it into recalcitrant forms that mimic the stability of the slow cycle. By engineering plants to produce decay-resistant biopolymers like suberin, or by using bacteria to precipitate carbon into mineral calcite (bio-concrete), biotechnology effectively slows down the return of carbon to the atmosphere, creating a net negative emissions effect.

4.2. The Engine of Capture: Biochemical Mechanisms of Photosynthesis

At the heart of all Bio-CCU strategies lies photosynthesis, the biological process that has regulated Earth's atmospheric composition for over 2.4 billion years. A nuanced understanding of this mechanism is the prerequisite for any biotechnological intervention. It is not merely "plants eating sunlight"; it is a complex series of redox reactions that constitute the primary entry point for energy into the biosphere.

4.2.1. The Photochemical Phase: Harvesting Energy

The process initiates in the thylakoid membranes of the chloroplast, where light energy is converted into chemical potential. This "Light-Dependent Reaction" is the power plant of the cell.

- **Photosystem II (PSII) and Water Splitting:** The reaction begins when photons strike the antenna complex of Photosystem II. This energy excites electrons to a higher energy state.
- **Electron Transport and ATP Synthesis:** The excited electrons travel through an Electron Transport Chain (ETC), passing through the cytochrome b6f complex. This passage pumps further protons into the thylakoid lumen. The resulting proton motive force drives the ATP Synthase enzyme, acting like a molecular turbine to synthesise Adenosine Triphosphate (ATP).
- **Photosystem I (PSI) and NADPH:** The electrons eventually reach Photosystem I, where they are re-energised by additional photons. These high-energy electrons are ultimately used to reduce NADP⁺ to NADPH.

Biotechnological Insight: The efficiency of these light reactions is remarkably high; plants capture quantum

energy with immense precision. The limitation in carbon capture rarely lies here. Instead, the bottleneck is almost always the downstream utilisation of this chemical energy in the "Dark Reactions".

4.2.2. The Calvin-Benson Cycle: The Carbon Fixation Engine

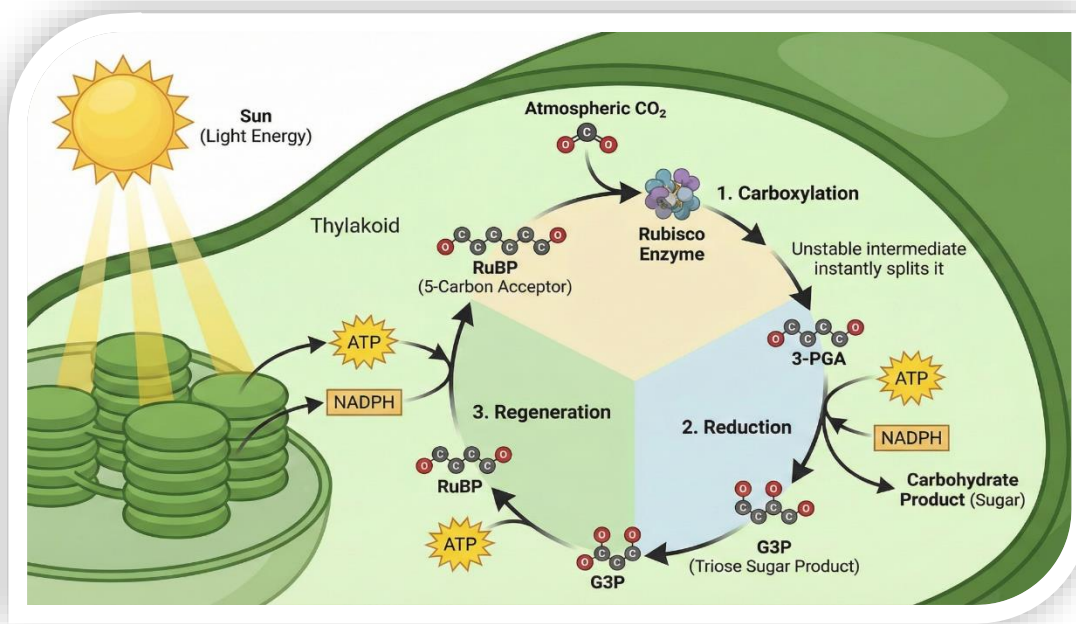


Figure 31. The Calvin-Benson Cycle

The chemical energy (ATP and NADPH) generated in the thylakoids is utilised in the stroma to fix atmospheric CO₂ into organic molecules. This cycle, known as the Calvin-Benson Cycle (or the Light-Independent Reactions), is the primary target for bioengineering.

The cycle proceeds in three distinct phases:

1. **Carboxylation:** The enzyme **Rubisco** (Ribulose-1,5-bisphosphate carboxylase/oxygenase) catalyses the attachment of a CO₂ molecule to a 5-carbon sugar acceptor, Ribulose-1,5-bisphosphate (RuBP). This forms an unstable 6-carbon intermediate that instantly splits into two molecules of 3-phosphoglycerate (3-PGA).
2. **Reduction:** ATP phosphorylates the 3-PGA, and NADPH reduces it, converting the molecule into Glyceraldehyde-3-phosphate (G3P), a simple triose sugar. This is the actual carbohydrate product of photosynthesis.
3. **Regeneration:** For the cycle to continue, the majority of the G3P molecules must be recycled and rearranged, consuming more ATP, to regenerate the RuBP acceptor.

4.2.3. The Rubisco Paradox: Evolutionary Flaws and Opportunities

Rubisco is frequently cited as the most abundant protein on Earth, yet it is notoriously inefficient. It acts as the primary gateway for carbon entry into the biosphere, but its catalytic rate is slow (processing only 3–10 molecules of CO₂ per second compared to thousands for other enzymes).

More critically, Rubisco suffers from a lack of specificity. It evolved in an ancient atmosphere that was rich in CO₂

and devoid of O₂. As a result, the enzyme's active site cannot perfectly discriminate between carbon dioxide and oxygen. When Rubisco binds CO₂ instead of CO₂, it initiates photorespiration.

The Cost of Photorespiration:

- Instead of producing two molecules of 3-PGA (productive), the oxygenation reaction produces one molecule of 3-PGA and one molecule of 2-phosphoglycolate (2-PG).
- 2-PG is toxic to the plant and must be recycled through a long, energy-expensive pathway involving the peroxisome and mitochondrion.
- Critically, this recycling process releases previously fixed CO₂ back into the atmosphere, undoing the work of photosynthesis.
- In typical C₃ plants (like wheat, rice, and soybeans), photorespiration can reduce photosynthetic efficiency by 25–30%, a loss that increases with temperature.

Table 8. Comparative Efficiency of Photosynthetic Pathways

Feature	C ₃ Photosynthesis	C ₄ Photosynthesis	CAM Photosynthesis
Primary Carboxylase	Rubisco	PEP Carboxylase (then Rubisco)	PEP Carboxylase (then Rubisco)
Photorespiration	High (20-30% loss)	Negligible	Negligible
Water Use Efficiency	Low	Moderate	High
Typical Plants	Wheat, Rice, Trees, Soybeans	Corn, Sugarcane, Sorghum	Cacti, Agave, Pineapple
Mechanism	Direct fixation in the mesophyll	Spatial separation (Bundle Sheath)	Temporal separation (Night/Day)
Relevance to Bio-CCU	Target for improvement (e.g., bypass)	Model for high efficiency	Model for arid land cultivation

4.3. Biotechnology-Based Climate Mitigation Strategies through CCU

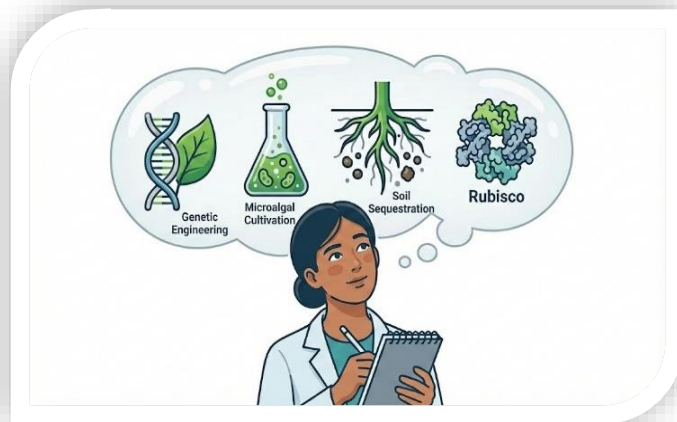


Figure 32. Strategies for Increasing the Carbon Capture

4.3.1. Advanced Plant Biotechnology for Climate Mitigation

Given the limitations of natural photosynthesis, biotechnologists are employing genetic engineering and synthetic biology to enhance the carbon capture capacity of plants.

This research focuses on two primary domains: increasing the rate of capture (Source Strength) and improving the permanence of storage (Sink Strength).

4.3.1.1. Engineering Photosynthetic Pathways: The "Turbocharged" Plant

Research is currently moving beyond simple selection breeding toward precise genetic interventions to overcome the Rubisco bottleneck.

The Photorespiratory Bypass:

Scientists are engineering "shunts" or alternative metabolic pathways inside plant cells. These synthetic pathways break down the toxic phosphoglycolate inside the chloroplast itself, rather than transporting it out to other organelles. This releases the CO₂ immediately adjacent to Rubisco, effectively creating a localized CO₂ pump that suppresses further oxygenation. Recent studies using genes from bacteria (*E. coli*) and pumpkin (*Cucurbita*) have demonstrated biomass increases of up to 40% in field-tested tobacco plants.

Synthetic Carbon Fixation Cycles:

Beyond optimising the Calvin cycle, synthetic biologists are designing entirely new metabolic cycles that do not exist in nature. The **CETCH cycle** (Crotonyl-CoA/Ethylmalonyl-CoA/Hydroxybutyryl-CoA), for instance, was constructed *in vitro* using enzymes from bacteria, archaea, and plants (Schwander et al., 2016). It uses Enoyl-CoA Carboxylases/Reductases (ECRs), which are carboxylating enzymes far faster and more specific than Rubisco. The CETCH cycle is theoretically 2-3 times more energy-efficient than the Calvin cycle. While currently a microbial proof-of-concept, translating such cycles into plants is a long-term "moonshot" goal for deep decarbonization.

4.3.1.1. The Salk Institute's Harnessing Plants Initiative (HPI)

One of the most prominent real-world applications of these principles is the Salk Institute's HPI, which focuses not just on capturing carbon but on keeping it in the ground. This initiative represents a shift from "carbon neutral" agriculture to "carbon negative" agriculture.

The "Salk Ideal Plant" Phenotype:

The initiative focuses on three key phenotypic traits to enhance carbon sequestration:

1. **Root Depth:** Deeper roots deposit carbon in lower soil strata. In topsoil, microbial activity is high, and carbon is quickly respired back to the atmosphere. Deep soil layers are often oxygen-poor, slowing decomposition and increasing the residence time of the carbon from years to centuries.

2. **Root Mass:** Increasing the sheer volume of root biomass creates a larger physical reservoir for captured carbon.
3. **Chemical Recalcitrance (Suberin):** This is the critical biochemical innovation. Suberin is a complex biopolymer (commonly known as cork) found in plant cell walls. It is a poly-aromatic/poly-aliphatic polyester that is highly resistant to enzymatic degradation by soil microbes. By genetically upregulating suberin production in roots, plants essentially become "carbon corks."

Genetic Targets and Translation: The HPI uses model plants like *Arabidopsis thaliana* and *Lotus japonicus* to identify the genes responsible for these traits, such as the *EXOCYST70A3* gene, which influences root system architecture and depth (Ogura et al., 2019). Once validated, these traits are transferred to major crop species like corn, soybean, rice, and wheat via CRISPR/Cas9 or advanced breeding. This approach leverages the massive scale of global agriculture—transforming millions of hectares of farmland into active carbon storage sites without reducing food yield.

4.3.1.3. The Rhizosphere and Soil Carbon Sequestration

Plants do not act alone; they exist in a symbiotic relationship with the soil microbiome. A significant portion of the carbon fixed by photosynthesis (up to 20-40%) is exuded from roots into the soil as sugars, amino acids, and organic acids. This "liquid carbon pathway" feeds soil microbes.

Biotechnology aims to engineer this plant-microbe interface (the rhizosphere). By selecting for plant varieties that exude specific compounds, scientists can encourage the growth of microbial communities that convert these exudates into stable Soil Organic Carbon (SOC) or mineral carbonates, rather than respiring it back as CO₂. This process, known as the "Microbial Carbon Pump," is essential for long-term sequestration (Jiao et al., 2010).

4.3.2. Microbial Systems: Algae and Cyanobacteria

While plants are the dominant terrestrial carbon sink, aquatic microorganisms (microalgae and cyanobacteria) offer higher photosynthetic rates and greater versatility for industrial integration. These organisms are responsible for roughly 50% of global biological carbon fixation despite representing a fraction of the biomass.

4.3.2.1. High-Efficiency Carbon Concentrating Mechanisms (CCMs)

Unlike land plants, many cyanobacteria have evolved sophisticated protein compartments called **carboxysomes**. These polyhedral structures encapsulate Rubisco and effectively isolate it from oxygen. Specific transporters actively pump bicarbonate into the cell, which then enters the carboxysome and is converted to high concentrations of CO₂. This creates a CO₂-saturated environment that allows Rubisco to operate at maximum velocity with negligible photorespiration.

Biotechnological Application

- **Transgenic Crops:** A major goal of current research is to transplant bacterial CCM genes (specifically the carboxysome shell proteins and bicarbonate transporters) into the chloroplasts of C3 crop plants. If successful, this could supercharge crop photosynthesis, potentially increasing yields by up to 60% while reducing water and nitrogen usage.

- **Industrial Photobioreactors:** Cyanobacteria can be grown in high-density bioreactors fed with industrial flue gas. Because they can tolerate higher CO₂ concentrations (up to 10-15%) than plants, they are ideal for "point-source" carbon capture at power plants or cement factories.

4.3.2.2. Recent Discoveries: The "Chonkus" Strain (UTEX 3222)

Scientific exploration of extreme environments continues to yield novel biological tools. Recently, researchers discovered a cyanobacterium strain (UTEX 3222), colloquially nicknamed "Chonkus," in volcanic seeps near Vulcano, Italy.

- **Characteristics:** This strain evolved in a high-CO₂, turbulent environment. It possesses two critical industrial traits: rapid growth in high carbon concentrations and a high cell density that causes it to sink rapidly in water.
- **The Harvesting Solution:** A major economic barrier to algal carbon capture is the energy cost of "dewatering"—separating the microscopic algae from the water, which typically requires energy-intensive centrifugation. The "Chonkus" strain's natural sinking ability allows for gravity-based harvesting, significantly reducing energy inputs and making the process economically viable.
- **Utilisation:** The harvested biomass can be dried and buried (permanent sequestration) or processed into biofuels, bioplastics, or animal feed, creating a circular carbon economy.

4.3.3. Carbon Utilisation in the Built Environment

Moving from biological mechanisms to application, the built environment represents a frontier for Bio-CCU. This sector involves integrating living systems into architecture and construction materials, transforming buildings from carbon emitters into carbon sinks.

4.3.3.1. Bio-Concrete and Bacterial Mineralisation

Concrete production is responsible for approximately 8% of global CO₂ emissions. Biotechnology offers a solution through Microbially Induced Calcite Precipitation (MICP) (DeJong et al., 2006).

Mechanism:

MICP relies on ureolytic bacteria such as *Sporosarcina pasteurii* or *Bacillus sphaericus*. These bacteria produce the enzyme urease, which catalyzes the hydrolysis of urea.

1. **Urea Hydrolysis:** The enzyme breaks down urea into ammonium and carbamate, which spontaneously degrades to ammonia and carbonic acid.
2. **pH Rise:** The ammonia molecules accept protons to form ammonium and hydroxide ions, significantly raising the local pH (alkalinity).
3. **Precipitation:** In this high-pH environment, carbonate ions accumulate. In the presence of soluble calcium ions, calcium carbonate precipitates out of solution. The bacterial cell wall often serves as the nucleation site for these crystals.

Applications:

- **Bio-Cement:** Companies like Biomason use this process to grow cement tiles and bricks at ambient temperatures. This eliminates the kiln-firing process of Portland cement (which requires temperatures of 1450°C), thereby removing the massive energy footprint and sequestering carbon in the mineral lattice of the brick.
- **Self-Healing Concrete:** Bacterial spores and nutrients (like calcium lactate) are embedded in the concrete mix. These spores remain dormant for decades. If the concrete cracks, water enters, activates the spores, and the bacteria begin to feed and precipitate calcite. This biological mortar seals the crack, restoring structural integrity and preventing rebar corrosion, thus extending the structure's lifespan and reducing the carbon cost of repairs.

4.3.3.2. *Bio-Facades and Microalgae Architecture*

Standard building facades are passive surfaces that often contribute to urban heat islands. Bio-facades transform them into active metabolic layers.

System Design:

Bio-facades consist of thin, transparent flat-panel photobioreactors (PBRs) mounted on the exterior of buildings. Water containing microalgae circulates through these panels.

- **Carbon Capture:** The algae absorb solar radiation and CO₂ (potentially fed from the building's heating system exhaust) to perform photosynthesis.
- **Energy Efficiency:** The biomass density shades the building, creating a dynamic insulation layer that reduces cooling loads in summer. The water absorbs solar heat, which can be harvested via heat exchangers to provide hot water for the building.
- **Case Study:** The BIQ (Bio-Intelligent Quotient) House in Hamburg, Germany, was the first pilot project to fully implement this technology. It demonstrated that bio-facades can capture significantly more carbon per square meter than terrestrial plants due to optimized growth conditions and lack of structural biomass (stems/trunks).

4.3.4. **Case Studies for Student Analysis**

To facilitate the "case analysis" requirement of the Erasmus+ project, the following section details three specific examples suitable for classroom deconstruction. These cases bridge the gap between theory and market reality.

Case Study 19: Green City Solutions - The CityTree



Figure 33. The CityTree

Overview:

A biotech startup based in Germany that combines Internet of Things (IoT) technology with moss cultures to address urban air pollution and carbon levels.

Technology:

The "CityTree" is a standalone vertical moss wall unit (approx. 4m tall). It uses specific moss species (like *Paulownia*) with massive surface areas to bind particulate matter and absorb CO₂, and includes automated irrigation, nutrient dosing, and sensors to maintain optimal moss health in harsh urban environments.

Claims:

The company claims that one unit can provide the air-purification benefit of up to 275 urban trees, filtering fine dust and cooling the surrounding air through evapotranspiration.

Critical Analysis for Students:

- Efficiency verification: Students should search for independent data on moss carbon uptake vs. tree uptake. Is the comparison to "275 trees" based on particulate filtration or carbon sequestration? (Usually filtration).
- Lifecycle Analysis (LCA): Does the manufacturing of the steel unit, the plastic components, and the electricity for the pumps negate the carbon savings?
- Urban design: How does "smart furniture" compare to planting real urban forests in terms of biodiversity, psychological benefits, and heat island mitigation?

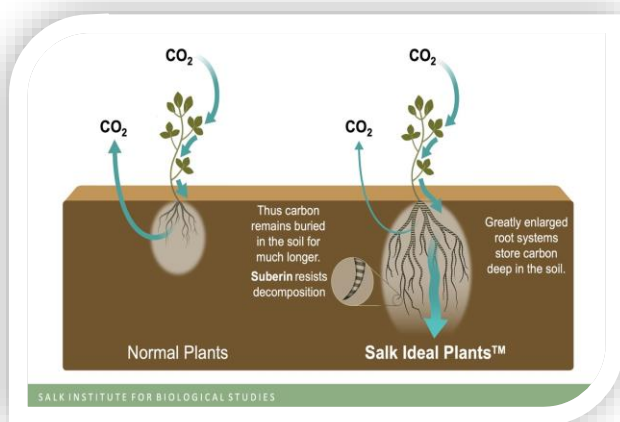


Figure 34. An Example of Genetic Engineering Approach to Carbon Sequestration.

- Agricultural Practice: How do modern farming practices (tilling vs. no-till) affect the stability of this deep-soil carbon? Tilling introduces oxygen, which accelerates microbial respiration of SOC.

Case Study 20: The Salk Ideal Plant™ (Deep Roots)

Overview:

As discussed in section 4.3.2, this is a genetic engineering approach to sequestration.

Data Context:

Soil holds about 2,500 gigatons of carbon, roughly three times the amount in the atmosphere. The "4 per 1000" initiative suggests that increasing soil carbon stocks by just 0.4% per year could halt the annual increase in atmospheric CO₂.

Student Inquiry:

- Recalcitrance: Explore the chemical stability of suberin. Why does it last longer than cellulose? (Aromatic rings vs. glucose chains).

Case Study 21: The Steelanol Project (Ghent, Belgium)



Figure 35. Industrial-scale facility to convert carbon-rich industrial waste gases into liquid fuel

Overview:

A flagship European project located at the ArcelorMittal steel plant in Ghent. It is the first industrial-scale facility in Europe to convert carbon-rich industrial waste gases into liquid fuel.

The challenge:

Steel manufacturing produces massive amounts of blast furnace gas (containing CO and CO₂). Traditionally, this gas is flared, releasing CO₂ directly into the atmosphere without creating value.

Biotech Solution:

- Recalcitrance: Explore the chemical stability of suberin. Why does it last longer than cellulose? (Aromatic rings vs. glucose chains).
- Agricultural Practice: How do modern farming practices (tilling vs. no-till) affect the stability of this deep-soil carbon? Tilling introduces oxygen, which accelerates microbial respiration of SOC.

Real-World Result:

Inaugurated in 2022, the facility has the capacity to produce **80 million litres of sustainable ethanol** annually. This product, branded as "Steelanol," is used to blend with gasoline for transport or as a feedstock for producing sustainable plastics, reducing annual CO₂ emissions by approximately 125,000 tonnes.



Figure 36. Inquiry about challenges in the area

Write your answers below.

1.

2.

3.

4.3.5. Student Research Framework: Methodologies and Protocols

This section provides the practical toolkit for Erasmus+ students to engage in "Science as Inquiry." It outlines how to access data, conduct literature reviews, and perform safe, meaningful experiments.

4.3.5.1. Accessing and Interpreting Climate Data



Figure 37. Inquiry about accession to climate data

For a project to be scientific, it must be grounded in data. Students should move beyond secondary sources to analyse primary climate datasets. Table 9 provides primary data sources for research

Table 9. Primary Data Sources for Student Research

Data Source	Description	Student Application
Hellenic National Meteorological Service (HNMS) - Greece http://www.hnms.gr	The official agency responsible for weather forecasting and climate observation in Greece.	Students can analyze historical climate data specific to the Mediterranean zone to understand heat stress impacts on crops (like olives), directly relating to heat-shock protein engineering discussed in the biotechnology section.
Turkish State Meteorological Service https://www.mgm.gov.tr	Turkey's official institution for weather and climate observation.	Students can access long-term temperature (TMAX/TMIN) and precipitation data for different regions of Turkey to analyze local climate change trends. This can be linked to the resilience of engineered plant genotypes (drought tolerance, pest resistance) discussed in the document.
Turkish Ministry of Environment, Urbanisation and Climate Change https://csb.gov.tr	Official portals containing national action plans for climate change, emission inventories, and environmental monitoring data.	Students can examine Turkey's greenhouse gas emission sectors and determine which areas offer potential for Bio-CCU technologies (e.g., Bio-Concrete or Algal Bioreactors for industrial flue gas).
Turkish Statistical Institute (TÜİK) - Environmental Statistics https://www.tuik.gov.tr/	National statistical data on energy, water usage, waste, and environmental pollution.	Provides the current economic and sectoral context needed for students to analyze the potential economic and environmental benefits of implementing Bio-CCU technologies (e.g., in agriculture or construction).
Croatian Meteorological and Hydrological Service (DHMZ) - Croatia https://meteo.hr	The national authority for meteorology, hydrology, and air quality monitoring in Croatia.	Students can compare climate trends between the Adriatic coast and continental Croatia, assessing how changing precipitation patterns affect biodiversity and water availability for biotechnological applications.

Slovenian Environment Agency (ARSO) - Slovenia https://www.arso.gov.si	The principal institution for monitoring the environment, nature, and water resources in Slovenia.	Provides comprehensive data on Alpine and sub-Mediterranean climate zones. Students can track long-term changes in temperature and soil moisture to propose suitable climate-resilient plant varieties for the region.
NOAA NCEI (National Centers for Environmental Information) https://www.ncei.noaa.gov/	Global historical weather and climate data.	Access local weather station data (GHCN-Daily) to analyze temperature trends (TMAX/TMIN) or precipitation changes in their specific Erasmus+ region over 50+ years.
NASA Earth Observations (NEO) https://neo.gsfc.nasa.gov/	Satellite imagery of vegetation health (NDVI), carbon monoxide, and temperature.	Visualize global photosynthesis patterns ("Green Up") and correlate them with seasonal CO ₂ fluctuations (the "Keeling Curve").
GLOBE Observer https://observer.globe.gov/	Citizen science app for tracking environmental changes.	Use the "Trees" tool to measure tree height and circumference, contributing to satellite calibration for biomass estimation.
IPCC Interactive Atlas https://interactive-atlas.ipcc.ch/	Regional climate projection tools from the 6th Assessment Report.	Explore future scenarios for their country under different warming pathways.
ESA Climate from Space https://cfs.climate.esa.int/index.html	Satellite-derived climate variables (ECVs).	Use the "Taking the Pulse of the Planet" resource pack to analyze soil moisture, fires, and vegetation cover changes in Europe.

4.3.5.2. Researching Scientific Literature



Figure 38. Inquiry about the tools for scientific literature research

A structured approach to literature review is essential.

Tools:

- **PubMed:** Ideal for biotechnology and genetic papers. Use MeSH (Medical Subject Headings) terms to refine searches.
- **Google Scholar:** Use "Advanced Search" to filter by year (e.g., "since 2020") to find the latest research on CRISPR or algae.

Some of the journals in the field:

1. Global Change Biology

- **Focus:** This journal publishes research that promotes understanding of the interface between biological systems and all aspects of environmental change (including climate change and atmospheric CO₂ increases).
- **Relevance for Students:** It is essential for understanding how biotechnological interventions (like enhanced photosynthesis) interact with the global carbon cycle and soil ecosystems.
- **Website:** <https://onlinelibrary.wiley.com/journal/13652486>

2. Nature Climate Change

- **Focus:** The world's most prestigious journal dedicated to climate change, covering both the physical science and the social/economic implications.
- **Relevance for Students:** An excellent source for visionary "Review" articles that discuss the potential of biological solutions (such as bio-energy with carbon capture) on a global policy scale.
- **Website:** <https://www.nature.com/nclimate>

3. Plant Biotechnology Journal

- **Focus:** An open-access journal publishing high-impact research on applied plant science, molecular biology, and genetics.
- **Relevance for Students:** Directly relevant to this chapter. Students can find technical details on drought-resistant transgenic crops, metabolic engineering for carbon fixation, and the use of plants as "bio-factories."
- **Website:** <https://onlinelibrary.wiley.com/journal/14677652>

4. Trends in Biotechnology (TIBTEC)

- **Focus:** Instead of raw data, this journal publishes concise reviews and opinions on the most exciting trends in biotechnology.
- **Relevance for Students:** Highly recommended for brainstorming project ideas. The articles are accessible and cover futuristic topics like synthetic biology for carbon capture and microbial cell factories.

- **Website:** <https://www.cell.com/trends/biotechnology/home>

5. Biotechnology for Biofuels and Bioproducts

- **Focus:** Focuses on the technological and operational aspects of converting plant biomass and captured carbon into fuels, chemicals, and materials.
- **Relevance for Students:** Critical for the "Utilisation" aspect of Bio-CCU. It provides insights into how the carbon captured by plants can be converted into economic value (Bio-economy).
- **Website:** <https://biotechnologyforbiofuels.biomedcentral.com>

Search Strategy: Students can use Boolean operators (AND, OR, NOT).

Example: "cyanobacteria" AND "carbon capture" NOT "marine" (to focus on freshwater or industrial applications).

Reading Guide (The Three-Pass Method):

Pass 1: Read title, abstract, and conclusions. Identify the "Big Question."

Pass 2: Analyze figures and tables. Do the data visualization support the abstract's claims.

Pass 3: Read methods and discussion for nuance and limitations.

Validity Check:

Lecturer trains students to distinguish between peer-reviewed journals (primary sources) and press releases or news articles (secondary sources).

Write your notes below:

4.3.6. Policy Framework and Future Outlook

Understanding science is insufficient without the political and economic context. The European Union has positioned itself as a global leader in the green transition, and Erasmus+ projects are expected to align with these strategic goals.

4.3.6.1. The Erasmus+ Context: Youth and the Green Transition

The European Union's Green Deal aims to make Europe the first climate-neutral continent by 2050. This ambitious goal relies heavily on the "Bioeconomy"—a renewable segment of the economy that uses biological resources from land and sea to produce food, materials, and energy. The Erasmus+ program plays a critical role in this transition by fostering "Green Skills" and critical thinking among European youth. This chapter aligns with the Action for Climate Empowerment (ACE) framework of the UNFCCC, which mandates that education is a pivotal tool in enabling society to make the deep structural changes required for sustainability.

Students engaging with this material are not merely passive learners; they are acquiring the competencies to become active participants in the Green Deal. Through the analysis of case studies and the execution of inquiry-based research, students develop the scientific literacy required to evaluate biotechnological solutions, distinguishing between genuine innovation and "greenwashing".

4.3.6.2. The European Green Deal and Bioeconomy

The European Green Deal is the overarching policy roadmap for the EU. It encompasses several strategies directly relevant to Bio-CCU:

- **Biodiversity Strategy 2030:** Includes a pledge to plant 3 billion trees. Biotechnology is vital here—not just for planting, but for selecting genotypes that are resilient to the future climate (drought tolerance, pest resistance) to ensure those trees survive to maturity.
- **Bioeconomy Strategy:** Focuses on replacing fossil-based materials with bio-based ones. This "circular bioeconomy" relies on the technologies discussed in this chapter (algae plastics, bio-concrete, timber construction) to close the carbon loop. It aims to reduce dependency on non-renewable resources while creating green jobs.
- **Just Transition Mechanism:** Ensures that the shift to a green economy is fair. For example, coal-dependent regions could be transitioned to hubs for algal biomass production or bio-energy, utilizing existing industrial infrastructure and workforce skills.

4.3.6.3. Youth Engagement: Action for Climate Empowerment (ACE)

The Erasmus+ program emphasizes democratic participation. Students should understand that their research contributes to the Action for Climate Empowerment (ACE) element of the Paris Agreement. ACE calls for empowering all members of society to engage in climate action through education, training, and public awareness.

By generating local data (e.g., through citizen science phenology tracking or tree carbon surveys), student groups can contribute to local climate adaptation plans, bridging the gap between classroom science and real-world policy. They move from being "students" to being "citizen scientists," actively monitoring the pulse of the planet.

4.4. Innovation Scenarios and Future Climate Projections

A review of recent scientific literature reveals a clear consensus for the future of Bio-CCU: the field must urgently transition from laboratory "proof-of-concepts" to scalable, economically viable industrial systems. For

undergraduate researchers, the literature recommends shifting focus from merely identifying natural organisms to actively engineering them using synthetic biology tools (such as CRISPR/Cas9) to enhance photosynthetic efficiency and tolerance to industrial stresses (e.g., high heat or pollutants). Furthermore, top-tier journals increasingly emphasise that biological success is not enough; future projects must integrate Techno-Economic Analysis (TEA) and Life Cycle Assessment (LCA) from day one. This means you must demonstrate that your proposed solution is not only scientifically novel but also energetically efficient and capable of delivering a true "carbon-negative" footprint when scaled up. Finally, the integration of computational biology and AI to predict enzyme behaviour and metabolic fluxes is highlighted as a critical skill for the next generation of biotechnologists.

Write your reflection on innovation scenarios below:

4.5. Conclusion

In conclusion, biotechnology for carbon capture and utilisation represents a transformative shift in climate mitigation, moving beyond simple emission reductions to actively removing and repurposing atmospheric carbon. By improving both natural and engineered biological systems, such as advanced plant phenotypes with enhanced root recalcitrance, we can create robust, carbon-negative value chains. However, the successful implementation of these innovations heavily depends on scaling them from laboratory prototypes to industrially and economically viable solutions. As future biotechnologists, it is important to integrate synthetic biology tools with techno-economic and life cycle assessments to ensure these technologies are both environmentally effective and sustainable. Ultimately, embracing this interdisciplinary approach will empower the next generation of scientists to actively shape climate policies and drive the global transition toward a circular, climate-resilient bioeconomy.

Chapter 5: Biotechnology for Ecosystem Restoration and Climate Crisis Mitigation

5.1. Nature-Based Solutions for Climate Adaptation

The climate crisis, environmental pollution, and increasing pressure on natural resources are among the most significant global challenges of the 21st century (Horn 2025). These processes contribute to ecosystem degradation, loss of biodiversity, and declining soil and water quality, ultimately threatening food security and environmental sustainability (Gabric 2023). As a result, there is a growing need for innovative and sustainable approaches that can support ecosystem restoration while simultaneously enhancing resilience to climate change.

Biotechnology offers a wide range of tools that can contribute to environmental protection, ecosystem restoration, and sustainable resource management (Karavolias et al., 2021). Various biotechnological strategies are being applied to restore degraded environments and improve ecosystem functioning. For example, phytoremediation uses plants to remove, stabilize, or transform contaminants in soil and water, representing an environmentally friendly method for remediation of polluted sites (Subašić et al., 2022). In addition, beneficial microorganisms, including plant growth-promoting bacteria, can be applied to enhance plant growth, improve nutrient uptake, and increase plant tolerance to abiotic stresses such as drought, salinity, and temperature extremes (Petrić et al., 2022). Seed priming techniques also play an important role in improving seed germination, plant establishment, and crop performance under unfavorable environmental conditions (Karalija et al., 2024). Furthermore, plant *in vitro* culture techniques have become valuable tools not only in plant propagation but also in environmental conservation and ecosystem restoration (Sota et al., 2025). *In vitro* methods enable the rapid multiplication of plant species, including endangered, rare, or ecologically important plants, which can later be reintroduced into degraded or threatened habitats. These techniques support biodiversity conservation and the restoration of plant populations, contributing to the recovery and stability of ecosystems.

Together, these biotechnological approaches support both the remediation of contaminated environments and the prevention of further ecosystem degradation by improving plant health, soil fertility, and ecosystem resilience. By strengthening plant adaptation to environmental stress and promoting sustainable management practices, biotechnology can play a key role in mitigating the impacts of climate change and supporting long-term ecosystem sustainability.

5.1.1. Biotechnology Approaches for Ecosystem Restoration and Climate Crisis Mitigation

5.1.1.1. Phytoremediation

Phytoremediation represents an environmentally friendly and cost-effective biotechnological approach used for the restoration of contaminated ecosystems. This method relies on the natural ability of certain plant species to absorb, accumulate, stabilize, or transform pollutants present in soil, water, and sediments (Subašić et al., 2022). Plants used in phytoremediation can remove contaminants such as heavy metals, pesticides, hydrocarbons, and other toxic compounds, thereby contributing to the gradual recovery of degraded environments. Different mechanisms of phytoremediation include phytoextraction, phytostabilization, phytodegradation, and rhizofiltration, each depending on the type of contaminant and environmental conditions (Subašić et al., 2022).

In addition to reducing pollution levels, phytoremediation contributes to ecosystem restoration by improving soil structure, increasing organic matter, and promoting microbial activity in the rhizosphere (Wu et al., 2022).

Vegetation cover established during the remediation process can also prevent soil erosion, enhance carbon sequestration, and support the re-establishment of local biodiversity.

Because of these multiple benefits, phytoremediation is increasingly recognized as a sustainable nature-based solution that can contribute both to ecosystem restoration and to the mitigation of some impacts associated with the climate crisis.

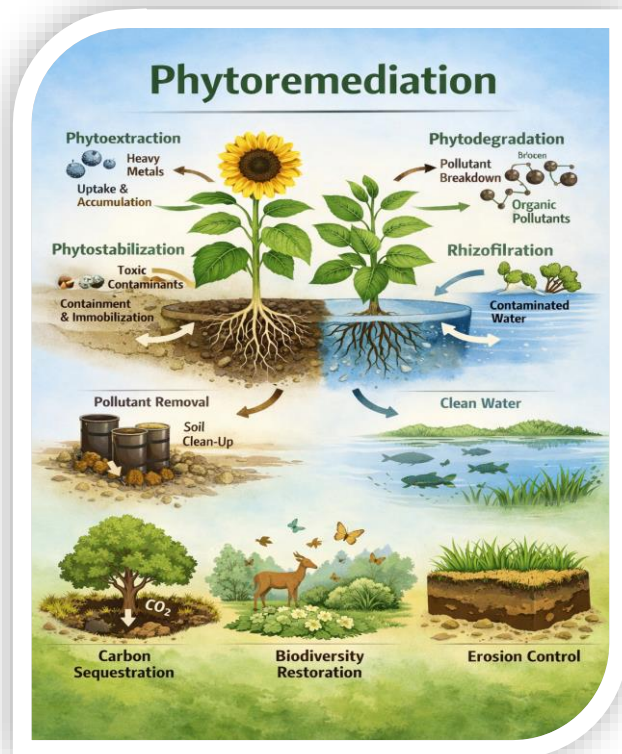


Figure 39. Schematic representation of phytoremediation mechanisms and potential applications in climate change mitigation

5.1.1.2. Beneficial Soil Microorganisms

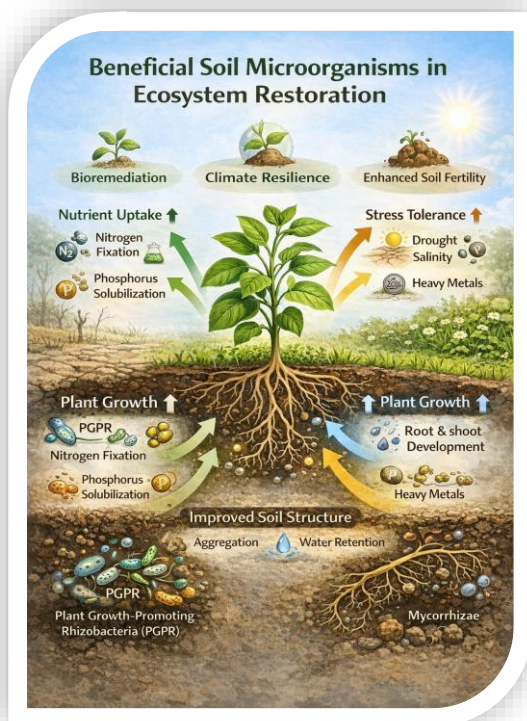


Figure 40. Schematic representation of the mechanisms of action of beneficial microorganisms and their potential applications in climate change mitigation

The use of beneficial soil microorganisms represents another important biotechnological strategy for ecosystem restoration and climate crisis mitigation. Soil is a complex and dynamic system inhabited by diverse microbial communities that play a crucial role in maintaining soil fertility, nutrient cycling, and plant health. Among these microorganisms, plant growth-promoting rhizobacteria (PGPR) are particularly important due to their ability to colonize plant roots and establish mutually beneficial relationships with plants (Petrić et al., 2022). These bacteria enhance plant growth, improve soil quality, and increase plant tolerance to environmental stresses such as drought, salinity, and heavy metal contamination.

Beneficial microorganisms support plant development through several mechanisms. Many bacteria produce phytohormones such as indole-3-acetic acid (IAA), which stimulates root growth and improves the plant's ability to absorb water and nutrients from the soil. Other microorganisms increase nutrient availability by fixing atmospheric nitrogen, solubilizing phosphorus, or producing siderophores that enhance iron uptake.

Additionally, some bacteria produce the enzyme ACC deaminase, which reduces stress-related ethylene levels in plants and helps them maintain growth under unfavourable environmental conditions (Senko et al., 2024).

Beyond their direct effects on plants, beneficial microorganisms also improve soil structure and ecosystem functioning (Chen et al., 2024). Many species produce extracellular polymers and biofilms that help stabilise soil aggregates, increase soil porosity, and enhance water retention in the rhizosphere. These changes create favourable microenvironments for plant roots and microbial communities, supporting plant establishment and resilience in degraded soils or areas affected by drought.

The application of microbial inoculants or microbial consortia is therefore increasingly used in sustainable agriculture and ecosystem restoration. By improving soil fertility, enhancing plant growth, and increasing tolerance to environmental stress, beneficial soil microorganisms contribute to the recovery of degraded ecosystems and help mitigate some of the impacts of climate change on agricultural and natural systems.

5.1.1.3. Seed Priming Techniques

Seed priming is a biotechnological approach designed to improve seed germination, seedling vigour, and overall plant establishment, particularly under stressful environmental conditions. This method involves treating seeds before sowing with physical, chemical, or biological agents to pre-activate metabolic processes (Figure 41), allowing seeds to germinate faster and more uniformly when sown. Seed priming has become a valuable tool in ecosystem restoration, sustainable agriculture, and climate crisis adaptation (Jatana et al., 2024).



Figure 41. Schematic representation of different seed priming techniques and their positive effects on plant growth and development

There are several types of seed priming techniques:

Hydropriming: Seeds are soaked in water for a controlled period to initiate pre-germination metabolic activity without allowing radicle emergence, enhancing germination rates and plant establishment in degraded or drought-prone soils.

Osmopriming: Seeds are treated with osmotic solutions, such as polyethylene glycol, to control water uptake and improve tolerance to salinity or drought. Osmoprimed seeds often exhibit better stress resilience and higher survival rates in challenging environmental conditions.

Biopriming: Seeds are treated with beneficial microorganisms, such as plant growth-promoting bacteria or fungi. This method enhances germination and supports plant growth, improves nutrient uptake, and increases resistance to pathogens and abiotic stress. **Hormonal priming:** Seeds are exposed to growth regulators like gibberellins or cytokinins, which activate specific metabolic pathways and improve seedling vigour, particularly under suboptimal environmental conditions.

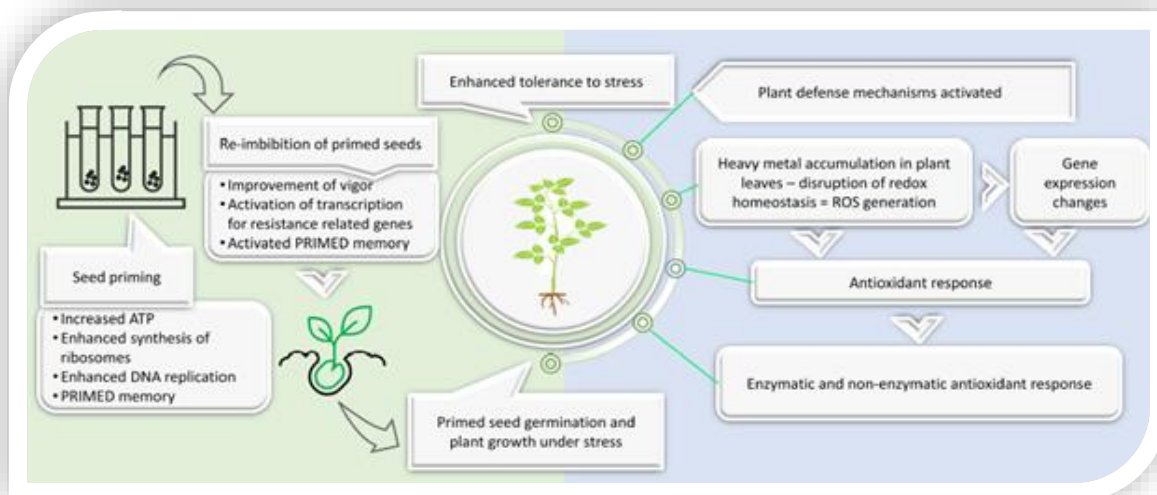


Figure 42. Schema of seed priming and its effects on plant stress tolerance (Karalija et al., 2022)

Seed priming techniques have been successfully applied in both agriculture and ecosystem restoration projects. For example, primed seeds of drought-tolerant species can be used to revegetate degraded lands, improve soil stabilisation, and accelerate ecosystem recovery. By enhancing early plant growth, seed priming increases the likelihood of seedling survival under stressful conditions such as drought, salinity, and poor soil fertility, which are increasingly common due to climate change (Karalija et al., 2024, 2026). Seed priming can also be used to increase the efficiency of other biotechnological approaches. For example, primed plants may exhibit a higher capacity for phytoremediation of polluted soils (Karalija et al., 2022).

Overall, seed priming represents a cost-effective and practical strategy to improve plant establishment, promote sustainable land management, and contribute to ecosystem resilience in the face of environmental challenges.

5.1.1.4. Plant In Vitro Culture Techniques

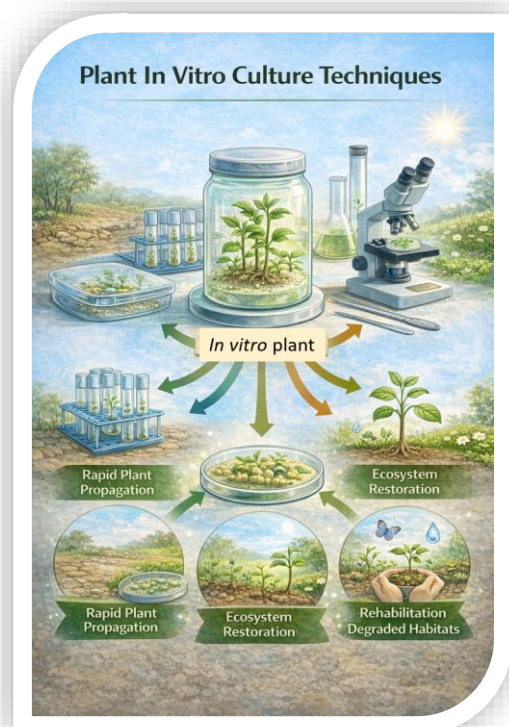


Figure 43. Potential application of in vitro plant cultures in mitigating the impacts of climate change

Plant in vitro culture techniques, also known as tissue culture, are advanced biotechnological methods used to propagate plants under controlled laboratory conditions (Yancheva & Kondakova 2018). These methods involve growing plant cells, tissues, or organs on nutrient media with precise control over light, temperature, and growth regulators (Figure 43). In vitro culture has become a powerful tool not only for rapid plant propagation but also for ecosystem restoration, conservation of endangered species, and rehabilitation of degraded habitats.

One of the main advantages of in vitro techniques is the ability to produce large numbers of uniform and disease-free plantlets in a relatively short period. This is particularly valuable for rare, endangered, or slow-growing plant species that are difficult to propagate by conventional methods. Example of ginkgo calus culture are at Figure 43. For ecosystem restoration, in vitro propagation allows the production of sufficient plant material for reintroduction into degraded areas, helping to restore vegetation cover, stabilise soils, and support local biodiversity.

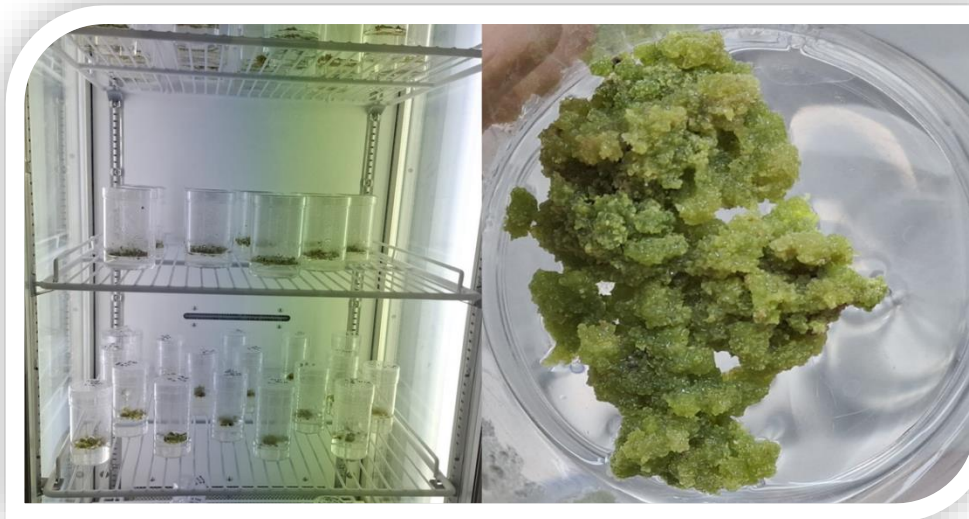


Figure 44. Plant in vitro culture growth chamber (left) and an example of Ginkgo callus culture (right)

Several *in vitro* approaches are commonly applied in restoration programs:

Micropropagation: Multiplication of shoots or plantlets from small explants to generate large numbers of genetically uniform plants for reintroduction into natural habitats.

Somatic embryogenesis: Production of embryos from somatic (non-reproductive) cells, enabling mass propagation and the development of stress-tolerant or genetically improved plant varieties.

Callus culture and organogenesis: Regeneration of complete plants from undifferentiated tissue (callus) or specific organs, allowing the recovery of plants from damaged or limited material.

Cryopreservation: Long-term storage of plant tissues or seeds at ultra-low temperatures, which is essential for preserving genetic diversity and safeguarding endangered species for future restoration efforts

In addition to restoration, in vitro culture techniques support research on plant responses to environmental stress, allowing scientists to select or develop varieties with improved tolerance to drought, salinity, or pollutants. By producing resilient plant material and enabling the reintroduction of ecologically important species, plant in vitro culture plays a critical role in ecosystem recovery, biodiversity conservation, and mitigation of the impacts of climate change.

5.2. Innovation Scenarios and Future Climate Projections

Climate change is expected to increase the frequency and intensity of extreme weather events, including floods, droughts, soil erosion, salinisation, and heatwaves. To prepare for these future challenges, students can explore innovative biotechnology-based strategies that enhance ecosystem resilience, prevent environmental degradation, and mitigate the impacts of climate-related disasters. By linking specific biotechnological methods to potential climate risks, students can develop practical and creative solutions with real-world applications.

Flood Risk Reduction

Approaches: Phytoremediation and plant–root biotechnology

Rationale: Deep-rooted and fast-growing plants can stabilize riverbanks, wetlands, and floodplains, reducing soil erosion and water runoff. Incorporating microbial consortia that promote root growth can enhance vegetation establishment and soil anchorage.

Student activity: Design an experimental restoration plan for a flood-prone area using combinations of native plants, microbial inoculants, and in vitro propagated seedlings to accelerate revegetation.

Write your plan below:

Soil Stabilisation and Erosion Control

Approaches: Soil-focused biotechnology using microbial consortia, bio-based soil stabilisers, and seed priming

Rationale: Beneficial microorganisms can strengthen soil aggregates, increase organic matter, and improve water retention, reducing vulnerability to erosion. Seed priming ensures successful plant establishment in degraded or unstable soils. Bio-based stabilisers (e.g., microbial polysaccharides) can further enhance soil cohesion.

Student activity: Investigate how microbial consortia and primed seeds can restore degraded slopes, agricultural terraces, or urban green spaces prone to erosion.

Write your investigation results below.

Drought and Salinity Resilience

Approaches: Seed priming, in vitro propagation of drought-tolerant species, and plant growth-promoting bacteria

Rationale: Primed seeds germinate faster and produce stronger seedlings under water-limited conditions. Microorganisms can enhance nutrient uptake and stress tolerance, while in vitro cultured plants allow the reintroduction of rare or resilient species.

Student activity: Propose a plant restoration experiment for arid or salinized lands, testing combinations of primed seeds, microbial inoculants, and tissue-cultured plants.

Write your proposal below.

Contaminated or Polluted Sites

Approaches: Phytoremediation and microbial-assisted remediation

Rationale: Plants combined with beneficial microbes can extract or stabilize heavy metals, hydrocarbons, and other pollutants, gradually restoring soil health.

Student activity: Design a bioremediation project using hyperaccumulator plants and selected microbial strains for a former industrial or mining site.

Outline your bioremediation project below.

Integrative “Multi-Hazard” Strategies

Proposal: Students can combine multiple methods to address overlapping climate risks, such as using in vitro propagated plants with microbial consortia to stabilize flood-prone soils while enhancing drought tolerance, or applying phytoremediation alongside bio-based soil stabilizers for polluted, erosion-prone lands.

Student activity: Develop scenario-based restoration plans under projected climate futures, assessing which combination of methods maximizes ecosystem resilience under multiple stressors.

Outline your scenario-based restoration plan/s below.

5.3. Case studies for student analysis

Case Study 22: Heavy Metal Remediation Using Sunflower

Strategy: Sunflower (*Helianthus annuus*) was cultivated on soils contaminated with heavy metals such as lead and cadmium. Due to its high biomass production and strong accumulation capacity, it was used in repeated planting cycles to progressively extract pollutants from the soil. The process was supported by basic soil management practices to enhance plant growth and metal uptake.

Results: Over time, a noticeable decrease in heavy metal concentrations in the topsoil was achieved. In addition, improvements in soil biological activity and structure were observed, indicating gradual ecosystem recovery. However, full remediation required multiple growing seasons.

Impact: This approach demonstrated a cost-effective and environmentally sustainable solution for rehabilitating contaminated land. It reduced ecological and human health risks and enabled the potential reuse of previously degraded areas for agriculture or ecological restoration.

Case Study 23: Use of PGPR for Improving Drought Tolerance in Crops

Strategy: Plant growth-promoting rhizobacteria (PGPR) were applied to seeds and soil in drought-prone agricultural systems. These microorganisms were selected for their ability to enhance root growth, improve nutrient availability, and regulate plant stress responses through phytohormone production and enzyme activity.

Results: Crops treated with PGPR showed enhanced root systems, improved water-use efficiency, and higher biomass under drought conditions compared to untreated plants. Soil quality also improved due to increased microbial activity and better nutrient cycling.

Impact: The use of beneficial microorganisms contributed to climate-resilient agriculture by reducing yield losses under drought stress. It also supported more sustainable farming practices by lowering dependence on chemical inputs and improving long-term soil health.

Case Study 24: Seed Priming for Crop Establishment under Salinity Stress

Strategy: Seeds were subjected to osmopriming using controlled osmotic solutions prior to sowing in saline soils. This treatment initiated early metabolic processes without completing germination, preparing the seeds for rapid and uniform emergence under stress conditions.

Results: Primed seeds exhibited faster germination rates, improved seedling vigor, and greater tolerance to salinity stress. Plants established more successfully and showed better early growth compared to non-primed controls.

Impact: Seed priming proved to be a simple and low-cost technique that enhances crop establishment in marginal environments. It supports adaptation to increasing soil salinization caused by climate change and contributes to stable agricultural productivity in vulnerable regions.

Case Study 25: Micropropagation for Restoration of Degraded Forest Ecosystems

Strategy: Native and ecologically important tree species were propagated using in vitro culture techniques to produce large numbers of uniform, disease-free plantlets. These plants were acclimatised and then transplanted into degraded forest areas requiring restoration.

Results: High survival rates and uniform growth patterns were observed in the field, particularly during the early stages of establishment. The availability of large quantities of planting material enabled efficient large-scale reforestation efforts.

Impact: *In vitro* propagation supported the restoration of degraded ecosystems by accelerating vegetation recovery and improving biodiversity conservation. It also contributed to climate mitigation through increased biomass production, enhanced carbon sequestration, and long-term ecosystem stabilisation.

Write your reflection on aforementioned case studies below:

5.4. Conclusion

Biotechnology offers a powerful and increasingly essential toolkit for addressing ecosystem degradation and the accelerating impacts of the climate crisis. The approaches discussed in this chapter, ranging from phytoremediation and beneficial soil microorganisms to seed priming and in vitro plant culture, demonstrate how biological systems can be harnessed to restore ecological balance and enhance resilience in both natural and managed environments.

Together, these methods highlight the importance of working with, rather than against, natural processes. Phytoremediation provides a sustainable means of removing or stabilizing environmental pollutants, while beneficial soil microorganisms support plant health, soil fertility, and carbon cycling. Seed priming techniques improve germination efficiency and stress tolerance, offering practical solutions for agriculture under changing climatic conditions. Meanwhile, plant in vitro culture techniques enable rapid propagation, conservation of genetic resources, and the development of stress-resistant plant varieties.

Although each approach is effective in its own right, their combined application represents a particularly promising strategy for large-scale ecosystem restoration and climate change mitigation. Continued advances in biotechnology, alongside interdisciplinary collaboration, will be crucial for optimizing these tools and ensuring their responsible implementation.

Ultimately, biotechnology does not replace ecological restoration efforts but strengthens them, providing innovative, scalable, and adaptable solutions for a more resilient and sustainable future.

Chapter 6: Innovation, Entrepreneurship, and Career Pathways in Climate-Oriented Biotechnology

6.1. Climate Innovation and Biotechnology Entrepreneurship

Climate change is no longer a distant or abstract issue. It is a challenge that today's biotechnology students will face directly in their professional lives. Biotechnology offers powerful tools to address climate-related problems, from reducing industrial emissions to developing sustainable materials and improving resource efficiency. Climate innovation means learning how scientific knowledge can be turned into practical solutions that respond to real environmental needs. It is not only about discovering new technologies, but also about understanding where and how these technologies can make a meaningful difference.

6.1.1. How Agricultural Biotechnology is Approached in the Greece, Croatia, Slovenia, and Türkiye

In Greece, agricultural entrepreneurship, including emerging fields such as agricultural biotechnology, is generally perceived through a dual lens shaped by tradition and innovation. On one hand, agriculture is strongly associated with cultural heritage, local food production, and environmental stewardship, which makes farmers and stakeholders cautious toward highly technological innovations such as biotechnology. On the other hand, increasing exposure to European Union bioeconomy strategies and sustainability challenges has strengthened the perception that innovation and entrepreneurial thinking are necessary for the sector's future development. Research on Greek agricultural entrepreneurs shows that factors such as education, innovativeness, and internal motivation significantly influence perceptions of entrepreneurial success in agriculture, highlighting a gradual shift toward more innovation-oriented thinking in the sector (Petroopoulos et al., 2026).

At the same time, studies on agricultural professionals in Greece indicate a growing recognition of the importance of entrepreneurial and digital competencies for sustainable agricultural development, although formal education in bioeconomy-related fields is still limited. Overall, agricultural biotechnology entrepreneurship in Greece is understood as a promising but still emerging field that requires balancing technological innovation with strong cultural and environmental sensitivities (Pliakoura et al., 2021).

In Croatia, agricultural biotechnology entrepreneurship is generally perceived as an emerging but still structurally constrained field, shaped by a strong tension between innovation ambitions and traditional agricultural practices. While national strategies increasingly emphasize innovation and EU integration in the agro-food sector, the agricultural innovation system remains fragmented, with low levels of R&D investment and limited cooperation between stakeholders, which slows down entrepreneurial development in high-tech agricultural domains. As the OECD notes, "Croatia's agricultural innovation performance, while relatively low and subject to important regional disparities, is improving steadily," yet it still faces "low levels of public and private investments in agricultural research and development and skill gaps among farmers" (OECD, 2025).

At the same time, research on agricultural stakeholders highlights that innovation and entrepreneurship are recognized as necessary responses to structural challenges in the sector, where "entrepreneurial orientation involves innovation, market responsiveness, efficient resource management, and diversification of production and income sources" (VVEU Conference Proceedings, 2026). Taken together, these findings suggest that agricultural biotechnology entrepreneurship in Croatia is increasingly viewed as a strategic opportunity linked

to sustainability and competitiveness, but its adoption is moderated by institutional fragmentation, limited skills, and the dominance of traditional farming structures.

In Slovenia, agricultural biotechnology entrepreneurship is generally perceived as an emerging but still fragmented field that sits at the intersection of traditional agricultural practices and an increasingly innovation-driven bioeconomy agenda. While the country has strong natural and scientific potential, the transition toward a fully integrated bioeconomy is still ongoing, with structural limitations in coordination, scale, and commercialization. Studies highlight that Slovenia possesses significant bioeconomy resources, yet “the bioeconomy remains underutilized, facing challenges in primary bioeconomy sectors, their integration along value chains, uptake of industrial innovation, and institutional coordination” (Juvančič et al., 2023).

At the same time, the entrepreneurial dimension of agriculture is increasingly recognized, with evidence showing that “proactiveness is the most influential element of entrepreneurial orientation for farm performance,” indicating that innovation-driven behavior is already linked to better agricultural outcomes (Verhees et al., 2011). Overall, agricultural biotechnology entrepreneurship in Slovenia is perceived as a promising but still developing domain, where scientific capacity and entrepreneurial potential exist, yet stronger institutional support, scaling mechanisms, and knowledge transfer are needed to fully translate innovation into market-oriented bio-based solutions.

In Turkey, agricultural biotechnology entrepreneurship is generally perceived as a promising yet complex and still-developing field that sits at the intersection of scientific innovation, agricultural modernization, and structural institutional constraints. While biotechnology is increasingly recognized as a critical driver of sustainability, health, and food security, its entrepreneurial adoption is often shaped by systemic barriers such as limited R&D capacity, insufficient institutional coordination, and knowledge gaps within the agricultural sector. As highlighted in academic literature, biotechnology entrepreneurship is understood as “the sum total of all activities performed by a team of individuals working together over time to create an enterprise that creates and commercializes life-changing products through the fusion of scientific and commercial disciplines” (Seyhan, 2022).

At the same time, capacity-building studies emphasize that Turkey’s agricultural biotechnology development is strongly influenced by its geographical and structural positioning, benefiting from both regional connectivity and scientific potential, yet still requiring stronger innovation systems and policy support (Dobos & Karaali, 2003). Overall, agricultural biotechnology entrepreneurship in Turkey is perceived as an emerging opportunity area with high strategic importance, but its practical implementation is moderated by institutional limitations, uneven innovation capacity, and the need for stronger collaboration between academia, industry, and policy actors.

Biotechnology entrepreneurship will give you the opportunity to take an active role in this process. Becoming an entrepreneur does not necessarily mean starting a company immediately; it means thinking creatively, identifying real-world problems, and understanding how biotechnology solutions can be applied beyond the laboratory. You can help bridge the gap between research and real-life impact by developing skills in innovation, collaboration, and problem-solving.

6.2. Developing Biotech Startups for Climate and Disaster Solutions

One of the most important realities that biotechnology graduates should keep in mind is that success in tackling climate change depends not only on developing technically sound solutions, but also on ensuring that these

solutions are practical, scalable, and economically sustainable. A concept may perform exceptionally well in a laboratory setting, yet fail when applied at an industrial scale. Issues such as the availability of raw materials, the feasibility of large-scale production, the management of waste and by-products, and long-term energy costs must be considered from the very beginning. Biotechnology ideas that cannot be scaled effectively tend to appear weak and unattractive to investors.

6.2.1. Feasibility

For an entrepreneurial biotechnologist, the first instinct is often to ask, “Is this technically possible?” This question marks a critical starting point and should never be overlooked. However, successful entrepreneurs look beyond technical feasibility and also reflect on several key considerations:

- Can the idea be developed within a reasonable timeframe using existing scientific knowledge?
- Is it possible to move from laboratory scale to pilot and industrial-scale applications?
- Can the process be reproduced reliably and controlled consistently?

Ideas that are scientifically impressive but require ten years of intensive R&D often remain academic projects rather than viable business ventures. For this reason, business ideas should be shaped with these practical constraints in mind. In the market, many ideas appear innovative yet respond to no real demand. In contrast, biotechnology-based products and tools designed to address climate change are valued when they meet concrete needs in a realistic and effective way. As a result, a strong biotechnology business idea must originate from a genuine problem. An entrepreneurial biotechnologist should always ask the following questions:

- Whose daily life is made more difficult by this problem?
- Which aspect or impact of climate change is causing it?
- How is the problem currently addressed, and why is that solution insufficient?
- Is there someone who is truly willing to pay for a better solution?

These questions naturally guide individuals toward innovation and entrepreneurship. The final question is particularly critical in the climate and environmental fields, as many stakeholders acknowledge the problem, but only a limited number are prepared to invest financially in its solution.

Let's work through it together.

Before this, you may consider playing “Climate Impact Quick Game” and “Systems Mapping Mini Game”.

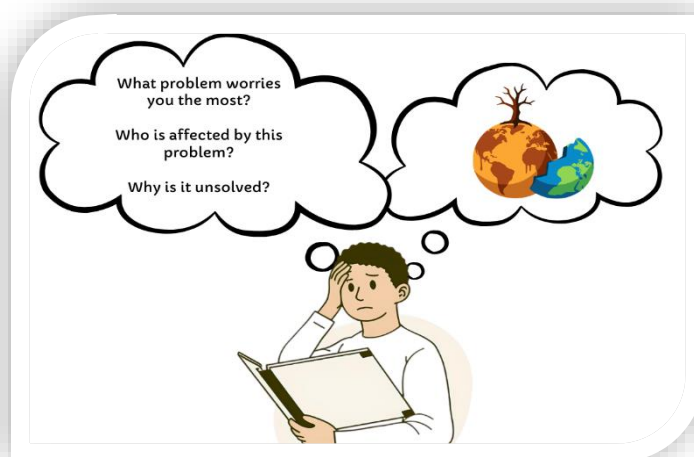
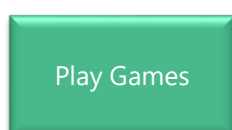


Figure 45. Inquiry about climate problems

1.

2.

3.

Read the thought bubble and reflect. But before this, you may consider playing the game “Biotechnology Solutions Challenge”.

Play Game

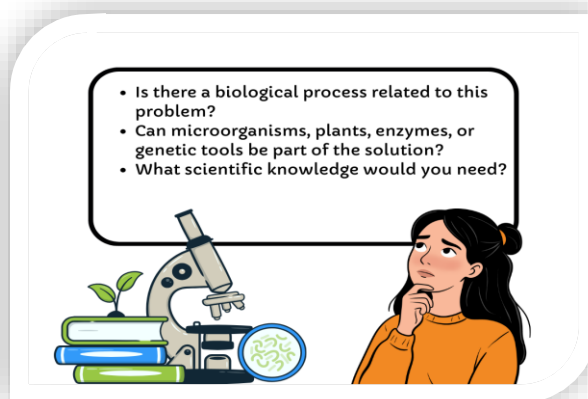


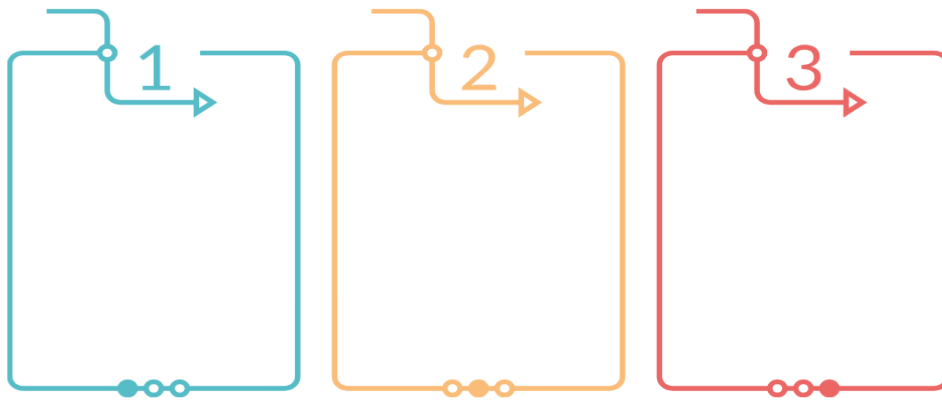
Figure 46. Inquiry about biotech solutions

1.

2.

3.

Write three possible solutions that you can offer



Read the question in the image and reflect. But before this, you may consider playing the game “Comparative Feasibility Lab”.

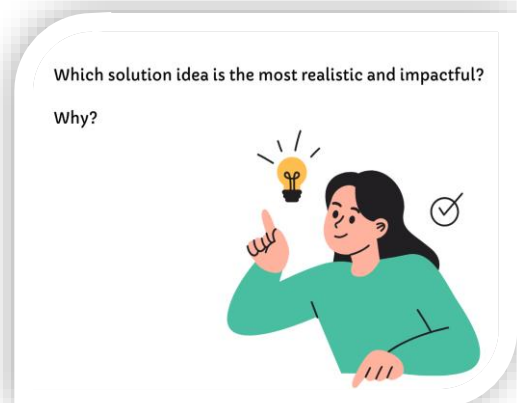
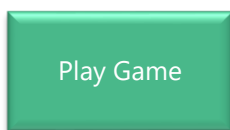


Figure 47. Inquiry about realistic and impactful solutions

Technical Difficulty:
Cost:
Implementation Time:
Environmental Risk:

Social Acceptance:

Scalability:

6.2.2. Competitiveness

Another essential question for any biotechnology business idea is whether it truly performs better than existing solutions. Statements such as “we are more environmentally friendly” or “we protect the environment” are rarely strong enough on their own to support investment, product development, or market adoption. Instead, the following factors play a decisive role in determining whether a solution will be accepted:

- Is it more cost-effective?
- Is it faster or more efficient?
- Does it require less energy, water, or raw materials?
- Is it easier to comply with legal and regulatory requirements?

It is important to note that biotechnology is closely intertwined with regulatory frameworks. Therefore, even at the idea stage, entrepreneurs should consider whether their product falls within the food, environmental, health, or industrial sectors, whether it requires lengthy approval or clinical processes, and whether existing regulations support or restrict the proposed technology. In many cases, a technically simpler and less “exciting” idea that faces fewer regulatory barriers can create impact much more quickly.

Let's continue with your idea



Figure 48. Inquiry about innovation in biotech solutions

Write your answers below.

6.2.3. Product Development and an Interdisciplinary Approach

Not every biotechnologist needs to develop a final consumer product. Viable outputs may include raw materials, byproducts, process technologies, analytical or measurement tools, or optimisation systems. Clearly defining where a product fits within the value chain helps prevent ideas from getting lost in the market and accelerates success.

Biotechnology projects often require collaboration across multiple disciplines. In such cases, entrepreneurs must be prepared to build strong teams or establish strategic partnerships. The most promising business ideas are those that allow for effective teamwork. Key questions to consider may include:

- Which disciplines are needed to bring this idea to life—engineering, software development, business development, law, or marketing?
- Which interdisciplinary or multidisciplinary collaborations are essential?

Let's look at how to turn an idea into a product.

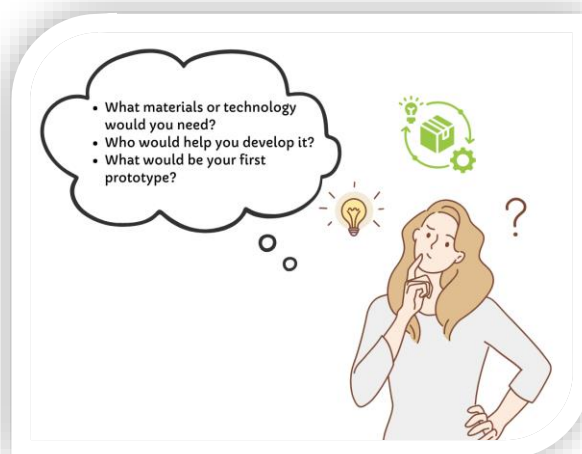


Figure 49. Inquiry about turning idea into a product

Write your answers below.

6.2.4. Why Now?

Finally, a strong idea is not only a good idea. It is one whose time has come. Entrepreneurs must closely monitor emerging regulations, cost trends, technological breakthroughs, and social and industrial shifts. Understanding why an idea is relevant now is often what transforms it from a concept into a successful innovation.

Employability and Transversal Skills for the Green and Sustainable Bioeconomy

Technical knowledge is essential in the field of biotechnology and will always remain a core requirement. However, in the green and sustainable bioeconomy, employability depends not only on technical expertise, but also on versatile, adaptable, and people-oriented skills.

Many entrepreneurs gain experience by working in different environments before turning their ideas into real applications. Career paths in the green and sustainable bioeconomy are rarely linear. A graduate may begin in the private sector and later move into public projects, transition from academia to entrepreneurship, or shift from R&D roles toward sustainability management or policy-related work.

In everyday working environments, employers increasingly value transversal skills such as effective communication, team leadership, adaptability, the ability to anticipate potential problems, and strong problem-solving capabilities. Organisations operating in the green and sustainable bioeconomy seek professionals who are technically competent but also comfortable working with uncertainty, capable of communicating across disciplines, and equipped with a clear sustainability perspective.

From this point of view, employability is shaped not only by what you know, but also by how you work. Biotechnology knowledge may open the door to a workplace, but transversal skills are what allow individuals to remain, grow, and progress within it. Like any other skill set, transversal skills can be learned and strengthened over time through conscious effort and active practice.

6.2.5. Transversal Skills

Transversal skills are not “extra” abilities; they are core competencies. In particular, during idea development and innovation processes within the green bioeconomy, the following transversal skills become especially important:

- **Critical thinking**

A key aspect of critical thinking is questioning whether a biotechnology solution truly delivers environmental benefits or merely appears “green.” A product being bio-based does not automatically make it sustainable. Without considering factors such as raw material sourcing, energy consumption, by-products, and long-term environmental impacts, solutions may remain superficial. A critical mindset helps distinguish genuinely sustainable innovations from those that only seem environmentally friendly.

- **Problem-solving**

Challenges in the green bioeconomy are often complex and multidimensional. For example, the biotechnological valorisation of agricultural waste involves not only technical processes, but also logistics, costs, regulations, and local implementation conditions.

Strong problem-solving skills enable individuals to break down this complexity into manageable elements and develop realistic, workable solutions.

- **Communication skills**

It is not sufficient for a biotechnology student to explain an idea only in academic terms. The same idea must often be communicated differently to investors, industry representatives, or public authorities. For instance, when presenting a biotechnology solution aimed at reducing carbon emissions, highlighting economic and environmental benefits rather than technical details can significantly increase the likelihood of implementation.

- **Teamwork and interdisciplinary collaboration**

Projects in the green bioeconomy are rarely confined to a single discipline. A biotechnology-based waste management solution, for example, may require collaboration between engineers, environmental experts, economists, and legal specialists.

Teamwork skills allow diverse perspectives to be combined, leading to stronger and more applicable outcomes.

- **Adaptability and openness to learning**

Climate policies, environmental regulations, and technologies evolve rapidly. A sustainability standard that is valid today may be revised within a few years. For this reason, being open to new knowledge, adapting quickly to changing conditions, and maintaining a lifelong learning mindset are critical transversal skills.

- **Sustainability and ethical awareness**

Solutions developed within the green bioeconomy have social impacts as well as environmental ones. The effects of a biotechnology product on local producers or issues related to fair access to natural resources should not be overlooked. Ethical awareness supports the development of solutions that gain long-term acceptance and societal trust.

Let's see your entrepreneurship-oriented transversal skills.

Rate yourself from 1 (very low) to 5 (very high):

Transversal Skills	Scale (Likert): 1: Very low; 2: Low; 3: Neutral; 4: High; 5: Very high				
Creativity	1	2	3	4	5
Problem-solving	1	2	3	4	5
Teamwork	1	2	3	4	5
Leadership	1	2	3	4	5
Communication	1	2	3	4	5
Risk-taking	1	2	3	4	5

6.2.6. Human and System Perspective

Sustainability cannot be achieved through technology alone; it operates through the interaction of human behaviour, economic structures, and policy frameworks. Employers, therefore, expect professionals to be able to assess environmental impacts, understand social and economic consequences, and act with a strong sense of responsibility and ethics. Likewise, those who plan to establish their own ventures in the future will seek these same qualities in the people they choose to work with.

Developing the wide range of skills required in this field goes beyond academic courses and grades. Project-based work, internships, volunteer activities, and participation in multinational and multicultural teams should begin as early as the undergraduate level to strengthen employability. This highlights the importance of active engagement rather than passive waiting—building networks, connecting with professionals who produce real value in the field, and maintaining ongoing communication. The green and sustainable bioeconomy needs not only skilled scientists but also professionals who can think critically, communicate effectively, take responsibility, and adapt to change. Transversal skills are the key that unlocks this future.

6.2.7. Exemplary Agrobiotech Initiatives

This section includes two good practices from agricultural biotechnology entrepreneurship.

Case Study 26: Twist Bioscience

<https://www.twistbioscience.com/>

Company Name: Twist Bioscience

Field of Work: Synthetic biology, genomics, and DNA synthesis



Figure 50. Twist Bioscience Website

Twist Bioscience is a biotechnology company founded by Emily Leproust. The company mainly works in synthetic biology and advanced DNA synthesis technologies. Its high-throughput DNA synthesis platform enables researchers to design and produce synthetic genes quickly and accurately. According to the source,

its work directly supports fields such as medicine, industrial chemicals, DNA data storage, and agricultural biology.

The company's products include synthetic DNA fragments, gene libraries, oligonucleotides, and tools for genome engineering. In the context of agricultural biotechnology, these products can support the development of drought-resistant crops, disease-resistant plant varieties, and enhanced nutritional traits in agricultural products.

Related topics this company could work on:

Give some examples of the topics this company (probably or could) work on, *e.g., CRISPR-based plant genome editing, sustainable crop improvement*

If you had founded a similar company, you would focus on:

Biotechnology Entrepreneurship Thinking Practice:

1. How can synthetic DNA technologies be commercialised for sustainable agriculture?
2. What agricultural problems can be solved through gene synthesis platforms?
3. How would you position such a biotech startup in the global food security market?

Reflect on your thinking:

Case Study 27: ADM Industrial Biosolutions

Company Name: ADM (Archer Daniels Midland) – Industrial Biosolutions

Field of Work: Agricultural biotechnology, industrial bioprocessing, plant-based biomaterials, and fermentation technologies

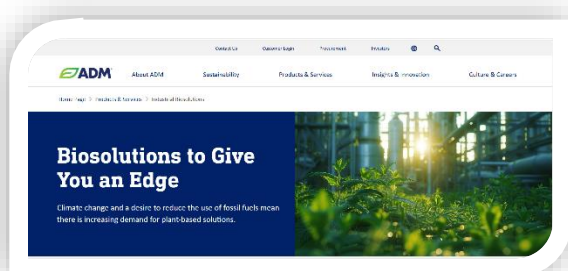


Figure 51. ADM Industrial Biosolutions Website

ADM Industrial Biosolutions is a biotechnology-driven industrial company that focuses on sustainable plant-based solutions. The company works at the intersection of agricultural biotechnology, industrial fermentation, renewable biomaterials, and sustainable farming systems.

The company's products cover a wide range of biotechnology-related applications, including fermentation nutrients, bio-based fertilisers, biodiesel, starches, industrial oils, pH buffers, plant-derived carbon and nitrogen sources, and agricultural support solutions. In particular, the fermentation products include glucose syrups, starches, soy and pea proteins, glycerin, and other plant-based feedstocks used in upstream and downstream biomanufacturing processes.

What innovative research areas you would be inclined to, if you had founded a similar company

Give some examples of the research areas your company would work on, *e.g., Stress memory bio-primers, etc.*

Biotechnology Entrepreneurship Thinking Practice:

1. How can plant-based industrial biotechnology contribute to sustainable agriculture?
2. Which agricultural by-products can be transformed into value-added biotechnological products?
3. How would you design a startup that combines fermentation biotechnology with plant health solutions?

Reflect on your thinking:

6.3. Conclusion

Agricultural biotechnology stands at an interesting intersection of science, sustainability, and human need. It is a field shaped not only by technological progress, but also by patience, responsibility, and the ability to work across disciplines.

For students interested in becoming bio entrepreneurs, curiosity may be just as valuable as expertise. Many meaningful innovations begin with simple observations, persistent questions, and the willingness to keep learning. Success in this area rarely comes from science alone; it often grows through collaboration, adaptability, and understanding real-world problems, encouraging entrepreneur candidates to listen, observe, and recognise the market's interests and inclinations.

The challenges surrounding food systems, climate, and agriculture are complex, and no single solution will solve them all. Yet thoughtful ideas, developed carefully and ethically, can still make a measurable difference over time. That is what makes this field especially valuable: it offers the possibility of creating innovations that are not only commercially meaningful, but also socially and environmentally relevant.

Beyond the Bench

A Closing Call to Action for the Climate-Driven Biotechnologist

You have reached the final pages of this guidebook. But in many ways, this is not an ending, it is a beginning. The knowledge you have built across these chapters, from the invisible microbial communities orchestrating soil fertility, to the enzymatic elegance of photosynthesis-based carbon capture, to the entrepreneurial frameworks that can transform a laboratory insight into a real-world climate solution, represents a foundation. What you do with that foundation is the more consequential question.

The climate crisis is not a problem that sits neatly within a single scientific discipline. It emerges from the intersection of biological systems, human decisions, economic structures, and policy environments, and it demands solutions built at exactly that same intersection. As a student of agricultural biotechnology, you are uniquely positioned at this crossroads. You understand living systems. You know how microorganisms communicate with roots, how gene expression responds to environmental stress, how fermentation can convert waste into resource. These are not academic curiosities. They are the building blocks of the next agricultural revolution.

The most urgent challenge of our time will not be solved by a single breakthrough in a single laboratory. It will be addressed by a generation of scientists who know how to think across boundaries — between disciplines, between sectors, and between today's constraints and tomorrow's possibilities.

What this guidebook has asked of you

Each chapter in this guidebook was designed not simply to deliver information, but to stretch your thinking. You were invited to consider how microbiome-based innovations can reshape food systems under a changing climate. You explored how circular bioeconomy principles can eliminate the very concept of waste from agricultural and industrial processes. You examined how the soil beneath a field is not inert ground, but a living system whose functioning depends on microbial diversity, spatial context, and the choices farmers and policymakers make every day.

You were also introduced to the science of carbon — how biological systems capture, fix, and potentially store it, and to the profound possibilities of biotechnology-assisted ecosystem restoration. And in the final chapter, you were asked to step outside the role of student and into the role of innovator: someone who can identify a genuine problem, assess the feasibility of a biological solution, understand competitive and regulatory landscapes, and communicate an idea to people who matter beyond the laboratory bench.

Microbiome literacy

Understanding soil and plant-associated microbial communities as agents of climate-smart agriculture

Circular thinking

Designing bio-based systems where waste becomes feedstock and every resource is valorised

Carbon intelligence

Deploying photosynthetic and microbial systems as tools for meaningful, scalable carbon capture

Entrepreneurial science

Translating technical expertise into ventures that generate ecological and economic value

Transversal skills

Critical thinking, collaboration, communication, and ethical awareness as core professional competencies

Systems perspective

Linking biological mechanisms to policy frameworks, market dynamics, and societal needs

The agricultural biotechnologist as a climate actor

Agricultural biotechnology occupies a particularly critical role in climate mitigation and adaptation. Agriculture is simultaneously one of the largest contributors to greenhouse gas emissions and one of the most vulnerable sectors to the consequences of a warming planet. It is also one of the few domains where biology, harnessed through biotechnology, can provide solutions at the scale and speed that the situation demands.

Biofertilisers that reduce dependency on synthetic nitrogen. CRISPR-assisted crop varieties with enhanced drought tolerance. Fermentation platforms that upcycle agricultural residues into biofuels, bioplastics, and nutraceuticals. Mycorrhizal networks that sequester carbon while improving soil structure. Cultured protein systems that decouple food production from land degradation. These are not distant possibilities — they are active areas of research, several of which you encountered directly in the pages of this guidebook.

What they have in common is that they all require the kind of scientist you are becoming: one who understands biological mechanisms deeply enough to engineer them responsibly, and broadly enough to communicate their value to farmers, investors, regulators, and communities. The technical knowledge you have developed is necessary. It is not, on its own, sufficient.

A biotechnology solution that cannot be explained to a farmer, funded by an investor, approved by a regulator, or trusted by a community is not yet a solution. It is a prototype. The distance between prototype and impact is where transversal skills, entrepreneurial thinking, and systems awareness live.

A note on uncertainty — and why it matters

One of the most honest things this guidebook has tried to convey is that the future of climate-oriented biotechnology is not fully written. The scenarios presented throughout each chapter were deliberately speculative in places, to train you in a skill that no textbook can provide in a single lesson: the capacity to think rigorously under uncertainty.

Climate projections involve ranges, not certainties. Regulatory landscapes will shift. New technologies will emerge and displace assumptions that seem settled today. The microorganism you are studying this semester may become the foundation of a product that does not yet exist. The policy framework shaping the bioeconomy in your country is likely to evolve substantially by the time you complete your degree. This is not a cause for anxiety, it is an invitation to remain a learner.

The most effective biotechnologists working on climate challenges today are not those who arrived with all the answers. They are those who developed the habit of asking better questions, building interdisciplinary networks, staying current with regulatory and market signals, and iterating quickly when initial assumptions proved wrong. This guidebook has attempted to cultivate exactly that orientation.

Your role in the European green transition

This guidebook was developed as part of the BIOSHIELD Erasmus+ project, bringing together universities and educational institutions from Greece, Türkiye, Slovenia, Croatia, and beyond. That collaborative geography is not incidental. The challenges of climate-oriented biotechnology are inherently transnational, and the green transition underway across Europe will require professionals who are comfortable working across cultural, institutional, and disciplinary boundaries.

The European Union's bioeconomy strategy, the Farm to Fork framework, and the Green Deal represent policy environments that are actively seeking the kind of knowledge and innovation that agricultural biotechnology can provide. As a graduate entering this landscape, you are not entering a sector in decline, you are entering one in rapid, complex, and consequential transformation. The demand for scientists who can bridge biology, sustainability, and entrepreneurship is growing. The question is whether you are ready to meet it.

Take the concepts from this guidebook into your next lecture, your next experiment, your next conversation with a supervisor or a peer. Ask yourself which of the biological systems you are studying could be redesigned for greater climate resilience. Ask what problem a local farmer, food producer, or municipality is facing that biotechnology might help to solve. Ask whether the research happening in your institution could be the seed of a startup, a policy recommendation, or a community intervention.

The climate does not wait for perfect conditions to act. Neither should you. You have the knowledge, the frameworks, and, if you have engaged seriously with this guidebook, the beginning of the mindset that climate-driven biotechnology demands. The bench is where science begins. The world is where it matters.

Go beyond the bench.

References

- Aasfar, A., Bargaz, A., Yaakoubi, K., Hilali, A., Bennis, I., Zeroual, Y., & Meftah Kadmiri, I. (2021). Nitrogen fixing *Azotobacter* species as potential soil biological enhancers for crop nutrition and yield stability. *Frontiers in Microbiology*, 12, 628379. <https://doi.org/10.3389/fmicb.2021.628379>
- Ahmed, A., & Makkawi, Y. (2025). The biorefinery paradigm: Technologies, feedstocks, and retrofitting for future sustainable energy. *Energies*, 18, 5919. <https://doi.org/10.3390/en18225919>
- Alam, A. M. M. N., et al. (2024). Sustainable scaffolding techniques for cultured meat development. *Food Research International*, 187, 114253. <https://doi.org/10.1016/j.foodres.2024.114253>
- Allen, R. E., Dodson, M. V., Luiten, L. S., & Boxhorn, L. K. (1985). A serum-free medium that supports the growth of cultured skeletal muscle satellite cells. *In Vitro Cellular & Developmental Biology*, 21, 636–640. <https://doi.org/10.1007/BF02623296>
- Allouzi, M. M. A., Allouzi, S. M. A., Keng, Z. X., Supramaniam, C. V., Singh, A., & Chong, S. (2022). Liquid biofertilizers as a sustainable solution for agriculture. *Heliyon*, 8(12), e12609. <https://doi.org/10.1016/j.heliyon.2022.e12609>
- Ambaru, B., Manvitha, R., & Madas, R. (2025). Synergistic integration of remote sensing and soil metagenomics data: Advancing precision agriculture through interdisciplinary approaches. *Frontiers in Sustainable Food Systems*, 8, 1499973.
- Baca-González, V., Asensio-Calavia, P., González-Acosta, S., Pérez de la Lastra, A., & Morales de la Nuez, A. (2020). Are vaccines the solution for methane emissions from ruminants? A systematic review. *Vaccines*, 8(3), 460. <https://doi.org/10.3390/vaccines8030460>
- Backer, R., Rokem, J. S., Ilangumaran, G., Lamont, J., Praslickova, D., Ricci, E., Subramanian, S., & Smith, D. L. (2018). Plant growth-promoting rhizobacteria: Context, mechanisms of action, and roadmap to commercialization of biostimulants for sustainable agriculture. *Frontiers in Plant Science*, 9, 1473. <https://doi.org/10.3389/fpls.2018.01473>
- Bardgett, R. D., & Caruso, T. (2020). Soil microbial community responses to climate extremes: Resistance, resilience and transitions to alternative states. *Philosophical Transactions of the Royal Society B: Biological Sciences*, 375(1794).
- Bardgett, R. D., & Van Der Putten, W. H. (2014). Belowground biodiversity and ecosystem functioning. *Nature*, 515(7528), 505–511.

- Barney, B. M., & Plunkett, M. H. (2022). Rnf1 is the primary electron source to nitrogenase in a high-ammonium-accumulating strain of *Azotobacter vinelandii*. *Applied Microbiology and Biotechnology*, 106, 5051–5061. <https://doi.org/10.1007/s00253-022-12059-x>
- Belkozhayev, A. M., Abaildayev, A., Kossalbayev, B. D., Tastambek, K. T., Kadirshe, D. K., & Toleutay, G. (2025). Microbial valorization of agricultural and agro-industrial waste into bacterial cellulose: Innovations for circular bioeconomy integration. *Microorganisms*, 13(12), 2686. <https://doi.org/10.3390/microorganisms13122686>
- Bello, S. K., Shobayo, A. B., Ibrahim, M. M., Alasinrin, S. Y., Aliyu, I. A., & Yusuf, A. A. (2021). Biological nitrogen fixation contributes to soil productivity in tropical agroecologies. *Nigerian Journal of Soil Science*, 31(1), 1–14. <https://doi.org/10.36265/njss.2020.310101>
- Ben-Arye, T., & Levenberg, S. (2019). Tissue engineering for clean meat production. *Frontiers in Sustainable Food Systems*, 3, 46. <https://doi.org/10.3389/fsufs.2019.00046>
- Ben-Arye, T., Shandalov, Y., Ben-Shaul, S., Landau, S., Zagury, Y., Ianovici, I., Lavon, N., & Levenberg, S. (2020). Textured soy protein scaffolds enable the generation of three-dimensional bovine skeletal muscle tissue for cell-based meat. *Nature Food*, 1(4), 210–220. <https://doi.org/10.1038/s43016-020-0046-5>
- Bender, S. F., Wagg, C., & van der Heijden, M. G. A. (2016). An underground revolution: Biodiversity and soil ecological engineering for agricultural sustainability. *Trends in Ecology & Evolution*, 31(6), 440–452. <https://doi.org/10.1016/j.tree.2016.02.016>
- Berg, G., Rybakova, D., Grube, M., & Köberl, M. (2015). The plant microbiome explored: Implications for experimental botany. *Journal of Experimental Botany*, 67(4), 995–1002. <https://doi.org/10.1093/jxb/erv466>
- Berruti, A., Lumini, E., Balestrini, R., & Bianciotto, V. (2016). Arbuscular mycorrhizal fungi as natural biofertilizers: Let's benefit from past successes. *Frontiers in Microbiology*, 6, 1559. <https://doi.org/10.3389/fmicb.2015.01559>
- Bhat, Z. F., Morton, J. D., Mason, S. L., & Bekhit, A. E. D. A. (2019). Technological, regulatory, and ethical aspects of cultured meat: A future slaughter-free harvest. *Comprehensive Reviews in Food Science and Food Safety*, 18(4), 1192–1208. <https://doi.org/10.1111/1541-4337.12473>
- Bhatia, S. K., Jagtap, S. S., Bedekar, A. A., Bhatia, R. K., Rajendran, K., Pugazhendhi, A., Rao, C. V., Atabani, A. E., Kumar, G., & Yang, Y. H. (2021). Renewable biohydrogen production from lignocellulosic biomass using fermentation and integration of systems with other energy generation technologies. *Science of the Total*

Environment, 765, 144429. <https://doi.org/10.1016/j.scitotenv.2020.144429>

- Blackstone, N. T., El-Abbadi, N., McClements, D. J., & Walsh, C. S. (2025). Guidelines for environmental life cycle assessment of cultivated meat. *The International Journal of Life Cycle Assessment*. <https://doi.org/10.1007/s11367-025-02562-4>
- Bolla, P. K., Panozzo, A., Minozzi, E., Valente, F., Potestio, S., Visioli, G., Martinez-Sañudo, I., & Vamerali, T. (2025). Effects of foliar-sprayed bio-fertilizer with N-fixing *Methylobacterium symbioticum* on morpho-physiological traits of maize under varying N fertilization rates. *Frontiers in Plant Science*, 16, 1661290.
- Bomkamp, S., Skaalure, S. C., Fernando, G. F., Ben-Arye, T., Swartz, E. W. E., & Specht, A. (2022). Scaffolding biomaterials for 3D cultivated meat: Prospects and challenges. *Advanced Science*, 9, 2102908. <https://doi.org/10.1002/advs.202102908>
- Brownlie, W. J., Sutton, M. A., Cordell, D., Reay, D. S., Heal, K. V., Withers, P. J. A., Vanderbeck, I., & Spears, B. M. (2023). Phosphorus price spikes: A wake-up call for phosphorus resilience. *Frontiers in Sustainable Food Systems*, 7, 1088776. <https://doi.org/10.3389/fsufs.2023.1088776>
- Brummer, E. C., Barber, W. T., Collier, S. M., Cox, T. S., Johnson, R., Murray, S. C., Olsen, R. T., Pratt, R. C., & Thro, A. M. (2011). Plant breeding for harmony between agriculture and the environment. *Frontiers in Ecology and the Environment*, 9, 561–568.
- Bryant, C. (2020). Consumer acceptance of cultured meat: An updated review (2018–2020). *Applied Sciences*, 10(15), 5201. <https://doi.org/10.3390/app10155201>
- Brzozowski, L., & Mazourek, M. (2018). A sustainable agricultural future relies on the transition to organic agroecological pest management. *Sustainability*, 10(6), 2023. <https://doi.org/10.3390/su10062023>
- Burrough, P. A., McDonnell, R. A., & Lloyd, C. D. (2015). *Principles of geographical information systems*. Oxford University Press.
- Cahyadi, E. R., Hidayati, N., Zahra, N., & Arif, C. (2024). Integrating circular economy principles into agri-food supply chain management: A systematic literature review. *Sustainability*, 16(16), 7165. <https://doi.org/10.3390/su16167165>
- Campisi, J., & d'Adda di Fagagna, F. (2007). Cellular senescence: When bad things happen to good cells. *Nature Reviews Molecular Cell Biology*, 8, 729–740. <https://doi.org/10.1038/nrm2233>
- Ceballos-Aguirre, N., Cuellar, J. A., Restrepo, G. M., & Sánchez, Ó. J. (2023). Effect of the application of *Gluconacetobacter diazotrophicus* and its interaction with nitrogen and phosphorus fertilization on

carrot yield in the field. *International Journal of Agronomy*, 2023, 6899532.

- Chakraborty, P., Kumar, R., Chakraborty, S., Saha, S., Chattaraj, S., Roy, S., Banerjee, A., Tripathy, S. K., Ghosh, A. K., & Jeon, B. H. (2024). Technological advancements in the pretreatment of lignocellulosic biomass for effective valorization: A review of challenges and prospects. *Journal of Industrial and Engineering Chemistry*, 137, 29–60. <https://doi.org/10.1016/j.jiec.2024.03.025>
- Chaudhary, A., Poudyal, S., & Kaundal, A. (2025). Role of arbuscular mycorrhizal fungi in maintaining sustainable agroecosystems. *Applied Microbiology*, 5(1), 6.
- Chen, Q., Song, Y., An, Y., Lu, Y., & Zhong, G. (2024). Soil microorganisms: Their role in enhancing crop nutrition and health. *Diversity*, 16, 734.
- Chriki, S., & Hocquette, J. F. (2020). The myth of cultured meat: A review. *Frontiers in Nutrition*, 7, 7. <https://doi.org/10.3389/fnut.2020.00007>
- Compant, S., Cassan, F., Kostić, T., Johnson, L., Brader, G., Trognitz, F., & Sessitsch, A. (2025). Harnessing the plant microbiome for sustainable crop production. *Nature Reviews Microbiology*, 23(1), 9–23. <https://doi.org/10.1038/s41579-024-01079-1>
- Cordell, D., Drangert, J.-O., & White, S. (2009). The story of phosphorus: Global food security and food for thought. *Global Environmental Change*, 19(2), 292–305. <https://doi.org/10.1016/j.gloenvcha.2008.10.009>
- Curtis, P. G., Slay, C. M., Harris, N. L., Tyukavina, A., & Hansen, M. C. (2018). Classifying drivers of global forest loss. *Science*, 361(6407), 1108–1111. <https://doi.org/10.1126/science.aau3445>
- de Abreu, V. H. S., Santos, A. S., & Monteiro, T. G. M. (2022). Climate change impacts on the road transport infrastructure: A systematic review on adaptation measures. *Sustainability*, 14(14), 8864. <https://doi.org/10.3390/su14148864>
- de Jesus Santos, A. F., & Da Cas Bundt, A. (2025). Foliar inoculation with *Methylobacterium symbioticum* SB23 enhances biological nitrogen fixation and maize yield under contrasting edaphoclimatic conditions. *Brazilian Journal of Agricultural Sciences/Revista Brasileira de Ciências Agrárias*, 20(2).
- DeJong, J. T., Fritzges, M. B., & Nüsslein, K. (2006). Microbially induced cementation to control sand response to undrained shear. *Journal of geotechnical and geoenvironmental engineering*, 132(11), 1381–1392.
- Delgado-Baquerizo, M., Singh, B. K., Liu, Y. R., Sáez-Sandino, T., Coleine, C., Muñoz-Rojas, M., Bastida, F., & Trivedi, P. (2025). Integrating ecological and evolutionary frameworks for SynCom success. *New*

Phytologist, 246(5), 1922–1933.

Devi, D. (2022). Soil microorganisms and their function to maintain soil fertility. In N. Kumar (Ed.), Chief Editor Dr Neeraj Kumar (pp. 61–75).

Dobos, E., & Karaali, A. (2003). Capacity building in agricultural biotechnology in Turkey. *Food Reviews International*, 19(4), 437–445. <https://doi.org/10.1081/FRI-120025484>

Duan, S., Feng, G., Limpens, E., Bonfante, P., Xie, X., & Zhang, L. (2024). Cross-kingdom nutrient exchange in the plant-arbuscular mycorrhizal fungus-bacterium continuum. *Nature Reviews Microbiology*, 22(12), 773–790. <https://doi.org/10.1038/s41579-024-01073-7>

Edelenbosch, O. Y., Hof, A. F., Van Den Berg, M., De Boer, H. S., Chen, H.-H., Daioglou, V., Dekker, M. M., Doelman, J. C., Den Elzen, M. G. J., Harmsen, M., Mikropoulos, S., Van Sluisveld, M. A. E., Stehfest, E., Tagomori, I. S., Van Zeist, W.-J., & Van Vuuren, D. P. (2024). Reducing sectoral hard-to-abate emissions to limit reliance on carbon dioxide removal. *Nature Climate Change*, 14(7), 715–722. <https://doi.org/10.1038/s41558-024-02025-y>

Eelager, M. P., Dalbanjan, N. P., Madihalli, S., Madar, M., Agadi, N. P., Korganokar, K., & Kiran, B. K. (2025). Pathways to a sustainable future: Exploring the synergy between sustainability and circular economy. *Sustainable Futures*, 10, 101208. <https://doi.org/10.1016/j.sftr.2025.101208>

Ezeagu, G., Omotosho, A., & Suleiman, K. (2023). Effective microorganisms, their products and uses—A review. *Nile Journal of Engineering and Applied Science*, 147954.

Fierer, N., & Jackson, R. B. (2006). The diversity and biogeography of soil bacterial communities. *Proceedings of the National Academy of Sciences*, 103(3), 626–631.

Food and Agriculture Organization of the United Nations. (2013). Tackling climate change through livestock: A global assessment of emissions and mitigation opportunities. FAO.

Food and Agriculture Organization of the United Nations. (2020). State of knowledge of soil biodiversity: Status, challenges and potentialities – Summary for policy makers. <https://doi.org/10.4060/cb1929en>

Food and Drug Administration. (2022). FDA completes first pre-market consultation for human food made using animal cell culture technology. <https://www.fda.gov>

Gabric, A. J. (2023). The climate change crisis: A review of its causes and possible responses. *Atmosphere*, 14, 1081.

- Garbin, V. P., Ferreira, G. A., Olegário, J. D. C., Poniewas, L., & de Macedo, R. E. F. (2025). Animal-derived components in cultivated meat research and their alternatives. *NPJ Science of Food*, 10(1), 7. <https://doi.org/10.1038/s41538-025-00656-9>
- Garcez de Oliveira Padilha, L., Malek, L., & Umberger, W. J. (2022). Consumers' attitudes towards lab-grown meat, conventionally raised meat and plant-based protein alternatives. *Food Quality and Preference*, 99, 104573. <https://doi.org/10.1016/j.foodqual.2022.104573>
- Geissdoerfer, M., Savaget, P., Bocken, N. M. P., & Hultink, E. J. (2017). The circular economy – A new sustainability paradigm? *Journal of Cleaner Production*, 143, 757–768. <https://doi.org/10.1016/j.jclepro.2016.12.048>
- Gervasi, T., & Mandalari, G. (2024). Valorization of agro-industrial orange peel by-products through fermentation strategies. *Fermentation*, 10(5), 224. <https://doi.org/10.3390/fermentation10050224>
- Gharechahi, J., Vahidi, M. F., Sharifi, G., Ariaeenejad, S., Ding, X.-Z., Han, J.-L., & Salekdeh, G. H. (2023). Lignocellulose degradation by rumen bacterial communities: New insights from metagenome analyses. *Environmental Research*, 229, 115925. <https://doi.org/10.1016/j.envres.2023.115925>
- Godfray, H. C. J., Aveyard, P., Garnett, T., Hall, J. W., Key, T. J., Lorimer, J., Pierrehumbert, R. T., Scarborough, P., Springmann, M., & Jebb, S. A. (2018). Meat consumption, health, and the environment. *Science*, 361(6399). <https://doi.org/10.1126/science.aam5324>
- González-Pérez, B. K., Rivas-Castillo, A. M., Valdez-Calderón, A., & Gayosso-Morales, M. A. (2022). Microalgae as biostimulants: A new approach in agriculture. *World Journal of Microbiology and Biotechnology*, 38(1), 4.
- González-Recio, O., López-Paredes, J., Ouatahar, L., Charfeddine, N., Ugarte, E., Alenda, R., & Jiménez-Montero, J. A. (2020). Mitigation of greenhouse gases in dairy cattle via genetic selection: 2. Incorporating methane emissions into the breeding goal. *Journal of Dairy Science*, 103(8), 7210–7221. <https://doi.org/10.3168/jds.2019-17598>
- Good Food Institute. (2025). The science of cultivated meat. <https://gfi.org/science/the-science-of-cultivated-meat/>
- Goodchild, M. F. (2018). A GIScience perspective on the uncertainty of context. *Annals of the American Association of Geographers*, 108(6), 1476–1481.
- Griffiths, H. M., Ashton, L. A., Parr, C. L., & Eggleton, P. (2021). The impact of invertebrate decomposers on plants and soil. *New Phytologist*, 231(6), 2142–2149. <https://doi.org/10.1111/nph.17553>

- Gstraunthaler, G. (2003). Alternatives to the use of fetal bovine serum: Serum-free cell culture. *ALTEX*, 20(4), 275–281. <https://doi.org/10.14573/altex.2003.4.257>
- Haque, M. N. (2018). Dietary manipulation: A sustainable way to mitigate methane emissions from ruminants. *Journal of Animal Science and Technology*, 60, 15. <https://doi.org/10.1186/s40781-018-0175-7>
- Harding, K. J., Turk-Kubo, K. A., Mak, E. W. K., Weber, P. K., Mayali, X., & Zehr, J. P. (2022). Cell-specific measurements show nitrogen fixation by particle-attached putative non-cyanobacterial diazotrophs in the North Pacific Subtropical Gyre. *Nature Communications*, 13(1), 6979. <https://doi.org/10.1038/s41467-022-34585-y>
- Harmesen, M. J. H. M., Van Vuuren, D. P., Bodirsky, B. L., Château, J., Durand-Lasserve, O., Drouet, L., & Fricko, O. (2019). The role of methane in future climate strategies: Mitigation potentials and climate impacts. *Climatic Change*, 163, 1409–1425.
- Hasanin, M. S., Abdelraof, M., Hashem, A. H., & El Saied, H. (2023). Sustainable bacterial cellulose production by *Achromobacter* using mango peel waste. *Microbial Cell Factories*, 22(1), 24. <https://doi.org/10.1186/s12934-023-02031-3>
- Hawkesford, M. J., Cakmak, I., Coskun, D., Kok, D., Lambers, L. J., Schjoerring, H., & White, J. K. (2023). Marschner's mineral nutrition of plants (Z. Rengel, I. Cakmak, & P. J. White, Eds.). Academic Press.
- Hengl, T., Mendes de Jesus, J., Heuvelink, G. B., Ruiperez Gonzalez, M., Kilibarda, M., Blagotić, A., Shangguan, W., Wright, M. N., Geng, X., & Bauer-Marschallinger, B. (2017). SoilGrids250m: Global gridded soil information based on machine learning. *PLoS ONE*, 12(2), e0169748.
- Herrero, M., Henderson, B., Havlik, P., Thornton, P., Conant, R., Smith, P., Wiersenius, S., Hristov, A., Gerber, P., Gill, M., Butterbach-Bahl, K., Valin, H., Garnett, T., & Stehfest, E. (2016). Greenhouse gas mitigation potentials in the livestock sector. *Nature Climate Change*, 6(5), 452–461. <https://doi.org/10.1038/nclimate2925>
- Horn, S. (2025). Climate change in the 21st century: Scientific evidence, risks, and adaptation pathways (pp. 1–6).
- Humbird, D. (2021). Scale-up economics for cultured meat. *Biotechnology and Bioengineering*, 118(8), 3239–3250. <https://doi.org/10.1002/bit.27848>
- Intergovernmental Panel on Climate Change. (2006). 2006 IPCC guidelines for national greenhouse gas inventories, Volume 4: Agriculture, Forestry and Other Land Use (AFOLU). IPCC.
- Intergovernmental Panel on Climate Change. (2021). Climate change 2021: The physical science basis.

Cambridge University Press. <https://www.ipcc.ch/report/ar6/wg1/>

Intergovernmental Panel on Climate Change. (2022). Climate change 2022: Mitigation of climate change (AR6 WGIII). Cambridge University Press.

Intergovernmental Panel on Climate Change. (2023). Climate change 2022 – Impacts, adaptation and vulnerability: Working Group II contribution to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press. <https://doi.org/10.1017/9781009325844>

Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services. (2019). Global assessment report on biodiversity and ecosystem services. IPBES.

Itelima, J. U., Bang, W. J., Onyimba, I. A., Sila, M. D., & Egbere, O. J. (2018). Bio-fertilizers as key player in enhancing soil fertility and crop productivity: A review. *Direct Research Journal of Agriculture and Food Science*, 6(3), 73–83.

Jangir, C. K., Kumar, S., & Meena, R. S. (2019). Significance of soil organic matter to soil quality and evaluation of sustainability. In R. S. Meena (Ed.), *Sustainable agriculture* (pp. 357–381). Scientific Publisher.

Jatana, B. S., Grover, S., Ram, H., & Baath, G. S. (2024). Seed priming: Molecular and physiological mechanisms underlying biotic and abiotic stress tolerance. *Agronomy*, 14, 2901.

Javed, Z., Tripathi, G. D., Mishra, M., & Dashora, K. (2021). Actinomycetes—The microbial machinery for the organic-cycling, plant growth, and sustainable soil health. *Biocatalysis and Agricultural Biotechnology*, 31, 101893.

Jiao, N., Herndl, G. J., Hansell, D. A., Benner, R., Kattner, G., Wilhelm, S. W., ... & Azam, F. (2010). Microbial production of recalcitrant dissolved organic matter: long-term carbon storage in the global ocean. *Nature Reviews Microbiology*, 8(8), 593–599.

Juvančič, L., Berne, S., Oven, P., & Osojnik Črnivec, I. G. (2023). Strategic concept paper for bioeconomy in Slovenia: From a patchwork of good practices to an integrated, sustainable and robust bioeconomy system. *Open Research Europe*, 3, 167. <https://doi.org/10.12688/openreseurope.16181.1>

Karalija, E., Dahija, S., Prijić, S., & Šamec, D. (2026). Enhancing chickpea (*Cicer arietinum* L.) resilience to salinity through proline and NaCl seed priming. *Phyton*, 95, 1–10.

Karalija, E., Lošić, A., Demir, A., & Šamec, D. (2024). Effects of seed priming on mitigating the negative effects of increased salinity in two varieties of sweet pepper (*Capsicum annuum* L.). *Soil Systems*, 8, 35.

Karalija, E., Selović, A., Bešta-Gajević, R., & Šamec, D. (2022). Thinking for the future: Phytoextraction of cadmium

using primed plants for sustainable soil clean-up. *Physiologia Plantarum*, 174(5), e13783.

- Karande, T. S., Ong, J. L., & Agrawal, C. M. (2004). Diffusion in musculoskeletal tissue engineering scaffolds: Design issues related to porosity, permeability, architecture, and nutrient mixing. *Annals of Biomedical Engineering*, 32(12), 1728–1743.
- Karavolias, N. G., Horner, W., Abugu, M. N., & Evanega, S. N. (2021). Application of gene editing for climate change in agriculture. *Frontiers in Sustainable Food Systems*, 5, 685801.
- Kavitha, S., Gondi, R., Kannah, R. Y., Kumar, G., & Banu, J. R. (2023). A review on current advances in the energy and cost effective pretreatments of algal biomass: Enhancement in liquefaction and biofuel recovery. *Bioresource Technology*, 369, 128383. <https://doi.org/10.1016/j.biortech.2022.128383>
- Ke, J., Wang, B., & Yoshikuni, Y. (2021). Microbiome engineering: Synthetic biology of plant-associated microbiomes in sustainable agriculture. *Trends in Biotechnology*, 39(3), 244–261. <https://doi.org/10.1016/j.tibtech.2020.07.008>
- Khan, I., Sun, J., Liang, W., Li, R., Cheong, K.-L., Qiu, Z., & Xia, Q. (2025). Innovations, challenges, and regulatory pathways in cultured meat for a sustainable future. *Foods*, 14, 3183. <https://doi.org/10.3390/foods14183183>
- Knychala, M. M., Boing, L. A., Ienczak, J. L., Trichez, D., & Stambuk, B. U. (2024). Precision fermentation as an alternative to animal protein, a review. *Fermentation*, 10(6), 315. <https://doi.org/10.3390/fermentation10060315>
- Kolkman, A. M., Van Essen, A., Post, M. J., & Moutsatsou, P. (2022). Development of a chemically defined medium for in vitro expansion of primary bovine satellite cells. *Frontiers in Bioengineering and Biotechnology*, 10, 895289. <https://doi.org/10.3389/fbioe.2022.895289>
- Kolur, S. M., Burud, A., Ramasamy, M., Sampath, V., Chellem, S. R., Satapathy, S. N., & Rout, A. (2024). A review on biotech innovations in seed technology for robust crop production. *Journal of Advances in Biology & Biotechnology*, 27(5), 535–550. <https://doi.org/10.9734/jabb/2024/v27i5816>
- Kour, D., Rana, K. L., Yadav, A. N., Yadav, N., Kumar, M., Kumar, V., Vyas, P., Dhaliwal, H. S., & Saxena, A. K. (2020). Microbial biofertilizers: Bioresources and eco-friendly technologies for agricultural and environmental sustainability. *Biocatalysis and Agricultural Biotechnology*, 23, 101487. <https://doi.org/10.1016/j.bcab.2019.101487>
- Kumar, S., Choudhary, M., K, J. R., Vishwakarma, V. K., Kashyap, V. K., Sahoo, S., & Mukhopadhyay, S. (2024). A

- review on the impact of climate change on plant pathogen interactions. *Journal of Advances in Microbiology*, 24(8), 11–27. <https://doi.org/10.9734/jamb/2024/v24i8843>
- Lee, Y. S., Yuan, M., Cai, R., Lim, K., & Minteer, S. D. (2020). Nitrogenase bioelectrocatalysis: ATP-independent ammonia production using a redox polymer/MoFe protein system. *ACS Catalysis*, 10(12), 6854–6861.
- Leiva, A., Larrea-Sebal, A., Acha, A., & Montes, L. R. (2025). Impact of biotechnology on sustainable development: An opinion analysis. *Sustainability*, 17(22), 10023. <https://doi.org/10.3390/su172210023>
- Lyu, D., Zajonc, J., Pagé, A., Tanney, C. A., Shah, A., Monjezi, N., Msimbira, L. A., Antar, M., Nazari, M., & Backer, R. (2021). Plant holobiont theory: The phytomicrobiome plays a central role in evolution and success. *Microorganisms*, 9(4), 675.
- Mączk, M., Gryta, A., & Frąc, M. (2020). Biofertilizers in agriculture: An overview on concepts, strategies and effects on soil microorganisms. In *Advances in Agronomy* (pp. 31–87). Elsevier.
- Maitan-Alfenas, G. P., Visser, E. M., & Guimarães, V. M. (2015). Enzymatic hydrolysis of lignocellulosic biomass: Converting food waste in valuable products. *Current Opinion in Food Science*, 1, 44–49. <https://doi.org/10.1016/j.cofs.2014.10.001>
- Malczewski, J., & Rinner, C. (2015). *Multicriteria decision analysis in geographic information science* (Vol. 1). Springer.
- Mariano, E., Jr., Lee, D. Y., Lee, J., Choi, Y., Park, J., Han, D., Kim, J. S., Park, J. W., Namkung, S., & Hur, S. J. (2024). A review on the characterization of edible scaffolds for cultured meat: Physical, chemical, biocompatibility, and food safety evaluation methods. *Food Chemistry*, 469, 142493. <https://doi.org/10.1016/j.foodchem.2024.142493>
- Martins, B., Bister, A., Dohmen, R. G. J., Gouveia, M. A., Hueber, R., Melzener, L., Messmer, T., Papadopoulos, J., Pimenta, J., Raina, D., Schaeken, L., Shirley, S., Bouchet, B. P., & Flack, J. E. (2024). Advances and challenges in cell biology for cultured meat. *Annual Review of Animal Biosciences*, 12, 345–368. <https://doi.org/10.1146/annurev-animal-021022-055132>
- Masson-Delmotte, V. et al. Global Warming of 1.5 °C. An IPCC Special Report on the Impacts of Global Warming of 1.5 °C Above Pre-Industrial Levels and Related Global Greenhouse Gas Emission Pathways, in the Context of Strengthening the Global Response to the Threat of Climate Change, Sustainable Development, and Efforts to Eradicate Poverty <https://www.ipcc.ch/sr15> (IPCC, 2018).
- Mattick, C. S., Landis, A. E., Allenby, B. R., & Genovese, N. J. (2015). Anticipatory life cycle analysis of in vitro biomass cultivation for cultured meat production in the United States. *Environmental Science &*

Technology, 49(19), 11941–11949. <https://doi.org/10.1021/acs.est.5b01614>

Messmer, T., Klevernic, I., Furquim, C., et al. (2022). A serum-free media formulation for cultured meat production supports bovine satellite cell differentiation. *Nature Food*, 3, 74–85. <https://doi.org/10.1038/s43016-021-00419-1>

Miranda, A. M., Hernandez-Tenorio, F., Villalta, F., Vargas, G. J., & Sáez, A. A. (2024). Advances in the development of biofertilizers and biostimulants from microalgae. *Biology*, 13(3), 199.

Mukherjee, R., & Sen, S. (2021). Role of biological nitrogen fixation (BNF) in sustainable agriculture: A review. *International Journal of Advancement in Life Sciences Research*, 4(3). <https://doi.org/10.31632/ijalsr.2021.v04i03.001>

OECD. (2025). *Policies for the future of farming and food in Croatia*. OECD Publishing. <https://doi.org/10.1787/011c6272-en>

Ogura, T., Goeschl, C., Filiault, D., Mirea, M., Slovak, R., Wolhrab, B., ... & Busch, W. (2019). Root system depth in *Arabidopsis* is shaped by EXOCYST70A3 via the dynamic modulation of auxin transport. *Cell*, 178(2), 400–412.

Pallucchini, M., Franchini, M., El-Ballat, E. M., Narraidoo, N., Pointer-Gleadhill, B., Palframan, M. J., Hayes, C. J., Dent, D., Cocking, E. C., Perazzolli, M., Fray, R. G., & Hill, P. J. (2024). *Gluconacetobacter diazotrophicus* AZ0019 requires functional *nifD* gene for optimal plant growth promotion in tomato plants. *Frontiers in Plant Science*, 15, 1469676. <https://doi.org/10.3389/fpls.2024.1469676>

Pallvi, & Gupta, H. (2025). Renewable composites for sustainable and eco-friendly solutions. *Composite Materials*, 9(2), 53–64. <https://doi.org/10.11648/j.cm.20250902.11>

Pendrill, F., Persson, U. M., Godar, J., & Kastner, T. (2019). Agricultural and forestry trade drives large share of tropical deforestation emissions. *Global Environmental Change*, 56, 1–10. <https://doi.org/10.1016/j.gloenvcha.2019.03.002>

Petrić, I., Šamec, D., Karalija, E., & Salopek-Sondi, B. (2022). Beneficial microbes and molecules for mitigation of soil salinity in Brassica species: A review. *Soil Systems*, 6, 18.

Petropoulos, D., Deirmentzoglou, G. A., Apostolopoulos, N., Paris, B., Michas, D., Balafoutis, A. T., Athanasopoulou, E., Nibbi, L., Li, H., Carvalho, L., Moreira da Silva, M. H., & Moreira da Silva, J. F. (2025). Digital and entrepreneurial competencies for the bioeconomy: Perceptions and training needs of agricultural professionals in Greece, Italy, Portugal, and Sweden. *Agriculture*, 15(10), 1106. <https://doi.org/10.3390/agriculture15101106>

- Pettorelli, N., Ryan, S., Mueller, T., Bunnefeld, N., Jędrzejewska, B., Lima, M., & Kausrud, K. (2011). The Normalized Difference Vegetation Index (NDVI): Unforeseen successes in animal ecology. *Climate Research*, 46(1), 15–27.
- Pliakoura, A., Beligiannis, G. N., Kontogeorgos, A., & Chatzitheodoridis, F. (2021). Farmers' perception of entrepreneurial success: Evidence from the Greek reality. *Agriculture*, 11(12), 1192. <https://doi.org/10.3390/agriculture11121192>
- Poore, J., & Nemecek, T. (2018). Reducing food's environmental impacts through producers and consumers. *Science*, 360(6392), 987–992. <https://doi.org/10.1126/science.aag0216>
- Post, M. J. (2012). Cultured meat from stem cells: Challenges and prospects. *Meat Science*, 92(3), 297–301. <https://doi.org/10.1016/j.meatsci.2012.04.008>
- Post, M. J., Levenberg, S., Kaplan, D. L., Genovese, N., Fu, J., Bryant, C., Negowetti, N., & Moutsatsou, P. (2020). Scientific, sustainability and regulatory challenges of cultured meat. *Nature Food*, 1(7), 403–415. <https://doi.org/10.1038/s43016-020-0112-z>
- Prisa, D., Fresco, R., & Spagnuolo, D. (2023). Microbial biofertilisers in plant production and resistance: A review. *Agriculture*, 13(9), 1666.
- Qi, Z., & Feng, R. (2025). Global natural and anthropogenic methane emissions with approaches, potentials, economic costs, and social benefits of reductions: Review and outlook. *Journal of Environmental Management*, 373, 123568. <https://doi.org/10.1016/j.jenvman.2024.123568>
- Quemada, M., Alonso-Ayuso, M., Esteban, R., & González, E. (2026). Maize (*Zea mays* L.) response to the biostimulant *Methylobacterium symbioticum* under various nitrogen fertilizer rates. *European Journal of Agronomy*, 172, 127887.
- Rahmati, S., Doherty, W., Dubal, D., Atanda, L., Moghaddam, L., Sonar, P., Hessel, V., & Ostrikov, K. K. (2020). Pretreatment and fermentation of lignocellulosic biomass: Reaction mechanisms and process engineering. *Reaction Chemistry & Engineering*, 5(11), 2017–2047. <https://doi.org/10.1039/d0re00241k>
- Rana, R. L., Bux, C., & Tommaso, V. (2026). The sustainability nexus of cultured meat: Integrating environmental, social, and technological-economic insights. *Food Research International*, 227, 118245. <https://doi.org/10.1016/j.foodres.2025.118245>
- Raza, S., Orooji, Y., Ghasali, E., Hayat, A., Karimi-Maleh, H., & Lin, H. (2023). Engineering approaches for CO₂ converting to biomass coupled with nanobiomaterials as biomediated towards circular bioeconomy.

- Rezaee Danesh, Y. (2025). Harnessing beneficial microbes and sensor technologies for sustainable smart agriculture. *Sensors*, 25(21), 6631.
- Risner, D., Kim, D. I., Choudhury, D., & Kaplan, D. L. (2024). Environmental impacts of cultured meat: A cradle-to-gate life cycle assessment. *ACS Food Science & Technology*. <https://doi.org/10.1021/acsfoodscitech.4c00281>
- Roque, B. M., Venegas, M., Kinley, R. D., de Nys, R., Duarte, T. L., Yang, X., & Kebreab, E. (2021). Red seaweed (*Asparagopsis taxiformis*) supplementation reduces enteric methane by over 80 percent in beef steers. *PLoS ONE*, 16(3), e0247820. <https://doi.org/10.1371/journal.pone.0247820>
- Rubio, N. R., Xiang, N., & Kaplan, D. L. (2019). Plant-based and cell-based approaches to meat production. *Nature Communications*, 10, 2046. <https://doi.org/10.1038/s41467-019-09255-2>
- Sadvakasova, A. K., Kossalbayev, B. D., Bauenova, M. O., Balouch, H., Leong, Y. K., Zayadan, B. K., & Allakhverdiev, S. I. (2023). Microalgae as a key tool in achieving carbon neutrality for bioproduct production. *Algal Research*, 72, 103096.
- Santander, C., González, F., Pérez, U., Ruiz, A., Aroca, R., Santos, C., Cornejo, P., & Vidal, G. (2024). Enhancing water status and nutrient uptake in drought-stressed lettuce plants (*Lactuca sativa* L.) via inoculation with different *Bacillus* spp. isolated from the Atacama Desert. *Plants*, 13(2), 158. <https://doi.org/10.3390/plants13020158>
- Satlewal, A., Agrawal, R., Bhagia, S., Sangoro, J., & Ragauskas, A. J. (2018). Natural deep eutectic solvents for lignocellulosic biomass pretreatment: Recent developments, challenges and novel opportunities. *Biotechnology Advances*, 36(8), 2032–2050. <https://doi.org/10.1016/j.biotechadv.2018.08.009>
- Schwander, T., Schada von Borzyskowski, L., Burgener, S., Cortina, N. S., & Erb, T. J. (2016). A synthetic pathway for the fixation of carbon dioxide in vitro. *Science*, 354(6314), 900-904.
- Seah, J. S. H., Singh, S., Tan, L. P., & Choudhury, D. (2022). Scaffolds for the manufacture of cultured meat. *Critical Reviews in Biotechnology*, 42(2), 311–323. <https://doi.org/10.1080/07388551.2021.1953456>
- Seibert, G. A., Feddern, V., Bastos, A. P. A., Kumar, A., & Verruck, S. (2025). Trends in non-animal scaffolds for cultured meat structuration. *NPJ Science of Food*, 9(1), 208. <https://doi.org/10.1038/s41538-025-00429-4>
- Senko, H., Kajić, S., Huđ, A., Palijan, G., Petek, M., Rajnović, I., Šamec, D., Udiković-Kolić, N., Mešić, A., Brkljačić, L.,

- & Petrić, I. (2024). Will the beneficial properties of plant-growth promoting bacteria be affected by waterlogging predicted in the wake of climate change: A model study. *Applied Soil Ecology*, 198, 105379.
- Seyhan, N. (2022). Weightening the barriers to biotechnology entrepreneurship in Turkey by SWARA method. *European Journal of Science and Technology*, 43, 136–141. <https://doi.org/10.31590/ejosat.1218377>
- Sganzerla, W. G., Tena-Villares, M., Buller, L. S., Mussatto, S. I., & Forster-Carneiro, T. (2022). Dry anaerobic digestion of food industry by-products and bioenergy recovery: A perspective to promote the circular economy transition. *Waste and Biomass Valorization*, 13(5), 2575–2589. <https://doi.org/10.1007/s12649-022-01682-4>
- Sharma, A., Negi, N. P., Narwal, P., Kumari, P., & Kumar, D. (2022). Arbuscular mycorrhizal fungi: A next-generation biofertilizer for sustainable agriculture. In R. Prasad & S.-H. Zhang (Eds.), *Beneficial microorganisms in agriculture* (pp. 161–176). Springer Nature Singapore. https://doi.org/10.1007/978-981-19-0733-3_6
- Sharma, M., Bains, A., Goksen, G., Dhull, S. B., Ali, N., Rashid, S., Elossaily, G. M., & Chawla, P. (2024). Valorization of agricultural waste for the synthesis of cellulose membranes. *International Journal of Biological Macromolecules*, 277, 134170.
- Singh, A., et al. (2022). Recent advances in bioengineered scaffold for in vitro meat production. *Biomaterials Science*, 10, 4088–4105. <https://doi.org/10.1039/D2BM00333A>
- Singh, D., Thapa, S., Geat, N., Mehriya, M. L., & Rajawat, M. V. S. (2021). Biofertilizers: Mechanisms and application. In *Biofertilizers* (pp. 151–166). Elsevier.
- Soice, E., & Johnston, J. (2021). Immortalizing cells for human consumption. *International Journal of Molecular Sciences*, 22, 11660. <https://doi.org/10.3390/ijms222111660>
- Sota, V., Nacheva, L., Bošnjak, D., Abraham, E., Jevremović, S., Cvjetković, B., Galović, V., Jevremović, D., Marković, Z., Kongjika, E., Bogunović, S., Zeljković, S., Andonovski, V., Daničić, V., & Vujović, T. (2025). Unveiling the Balkans' advances: In vitro biotechnology of woody plants in the early 21st century. *Frontiers in Plant Science*, 16, 1550318.
- Specht, L., Welch, D., Rees Clayton, E., & Lagally, C. (2018). Opportunities for applying biomedical production and manufacturing methods to the development of the clean meat industry. *Biochemical Engineering Journal*, 132, 161–168. <https://doi.org/10.1016/j.bej.2018.01.015>
- Stephens, N., Di Silvio, L., Dunsford, I., Ellis, M., Glencross, A., & Sexton, A. (2018). Bringing cultured meat to

market: Technical, socio-political, and regulatory challenges. *Trends in Food Science & Technology*, 78, 155–166. <https://doi.org/10.1016/j.tifs.2018.04.010>

Stout, A. J., Kaplan, D. L., & Flack, J. E. (2023). Cultured meat: Creative solutions for a cell biological problem. *Trends in Cell Biology*, 33(1), 1–4. <https://doi.org/10.1016/j.tcb.2022.10.002>

Subašić, M., Šamec, D., Selović, A., & Karalija, E. (2022). Phytoremediation of cadmium polluted soils: Current status and approaches for enhancing. *Soil Systems*, 6, 3.

Telles, T. S., Nogueira, M. A., & Hungria, M. (2023). Economic value of biological nitrogen fixation in soybean crops in Brazil. *Environmental Technology & Innovation*, 31, 103158. <https://doi.org/10.1016/j.eti.2023.103158>

Tenorio Berrío, R., Nelissen, H., Inzé, D., & Dubois, M. (2022). Increasing yield on dry fields: Molecular pathways with growing potential. *The Plant Journal*, 109(2), 323–341. <https://doi.org/10.1111/tpj.15550>

Tilman, D., Cassman, K. G., Matson, P. A., Naylor, R., & Polasky, S. (2002). Agricultural sustainability and intensive production practices. *Nature*, 418(6898), 671–677. <https://doi.org/10.1038/nature01014>

Timsina, J. (2018). Can organic sources of nutrients increase crop yields to meet global food demand? *Agronomy*, 8(10), 214. <https://doi.org/10.3390/agronomy8100214>

Trenberth, K. E. (2010). Changes in precipitation with climate change. *Climate Research*, 47, 123–138. <https://doi.org/10.3354/cr00953>

Trivedi, P., Batista, B. D., Bazany, K. E., & Singh, B. K. (2022). Plant–microbiome interactions under a changing world: Responses, consequences and perspectives. *New Phytologist*, 234(6), 1951–1959. <https://doi.org/10.1111/nph.18016>

Tuomisto, H. L., & Teixeira de Mattos, M. J. (2011). Environmental impacts of cultured meat production. *Environmental Science & Technology*, 45(14), 6117–6123. <https://doi.org/10.1021/es200130u>

Turganova, R., Tuleyeva, R., Belkozhaev, A., Gizatullina, N., Yelemessova, G., Taubatyrova, A., Mussalimova, M., Shynykul, Z., & Toleutay, G. (2025). Bacterial cellulose for sustainable food packaging: Production pathways, structural design, and functional modification strategies. *Polymers*, 17(23), 3165. <https://doi.org/10.3390/polym17233165>

United Nations. (n.d.). Sustainable Development Goals. <https://sdgs.un.org/goals>

van der Weele, C., & Tramper, J. (2014). Cultured meat: Every village its own factory? *Trends in Biotechnology*,

32(6), 294–296. <https://doi.org/10.1016/j.tibtech.2014.04.009>

- Vandenkoornhuyse, P., Quaiser, A., Duhamel, M., Le Van, A., & Dufresne, A. (2015). The importance of the microbiome of the plant holobiont. *New Phytologist*, 206(4), 1196–1206.
- Verbeke, W., Marcu, A., Rutsaert, P., Gaspar, R., Seibt, B., Fletcher, D., & Barnett, J. (2014). 'Would you eat cultured meat?' Consumers' reactions and attitude formation in Belgium, Portugal & the United Kingdom. *Meat Science*, 102, 49–58. <https://doi.org/10.1016/j.meatsci.2014.11.013>
- Verbeke, W., Sans, P., & Van Loo, E. J. (2015). Challenges and prospects for consumer acceptance of cultured meat. *Journal of Integrative Agriculture*, 14(2), 285–294. [https://doi.org/10.1016/S2095-3119\(14\)60884-4](https://doi.org/10.1016/S2095-3119(14)60884-4)
- Verhees, F. J. H. M., Kuipers, A., & Klopčič, M. (2011). Entrepreneurial proclivity and farm performance: The cases of Dutch and Slovenian farmers. *International Journal of Entrepreneurship and Innovation*, 12(3), 169–177. <https://doi.org/10.5367/ijei.2011.0039>
- Wahab, A., Muhammad, M., Munir, A., Abdi, G., Zaman, W., Ayaz, A., Khizar, C., & Reddy, S. P. P. (2023). Role of arbuscular mycorrhizal fungi in regulating growth, enhancing productivity, and potentially influencing ecosystems under abiotic and biotic stresses. *Plants*, 12(17), 3102.
- Wang, B., Li, Y., Wu, N., & Lan, C. Q. (2018). CO₂ bio-mitigation using microalgae. *Applied Microbiology and Biotechnology*, 102(2), 877–891. <https://doi.org/10.1007/s00253-017-8661-0>
- Wang, P., Yang, Y., Xue, D., Ren, L., Tang, J., Leung, L. R., & Liao, H. (2023). Aerosols overtake greenhouse gases causing a warmer climate and more weather extremes toward carbon neutrality. *Nature Communications*, 14(1), 5445. <https://doi.org/10.1038/s41467-023-42891-2>
- Wangsa Putrie, R. F., Aryantha, I. N. P., Iriawati, I., & Antonius, S. (2020). Diversity of endophytic and rhizosphere bacteria from pineapple (*Ananas comosus*) plant in semi-arid ecosystem. *Biodiversitas: Journal of Biological Diversity*, 21(7), 3084–3093. <https://doi.org/10.13057/biodiv/d210728>
- Willett, W., Rockström, J., Loken, B., Springmann, M., Lang, T., Vermeulen, S., Garnett, T., Tilman, D., DeClerck, F., Wood, A., Jonell, M., Clark, M., Gordon, L. J., Fanzo, J., Hawkes, C., Zurayk, R., Rivera, J. A., De Vries, W., Majele Sibanda, L., & Murray, C. J. L. (2019). Food in the Anthropocene: The EAT-Lancet Commission on healthy diets from sustainable food systems. *The Lancet*, 393(10170), 447–492. [https://doi.org/10.1016/S0140-6736\(18\)31788-4](https://doi.org/10.1016/S0140-6736(18)31788-4)
- Williams, A., Aguilar, M. R., Pattiya Arachchilage, K. G. G., Chandra, S., Rangan, S., Ghosal Gupta, S., & Artes Vivancos, J. M. (2024). Biosensors for public health and environmental monitoring: The case for

sustainable biosensing. *ACS Sustainable Chemistry & Engineering*, 12(28), 10296–10312.
<https://doi.org/10.1021/acssuschemeng.3c06112>

World Health Organization. (2025). The state of food security and nutrition in the world 2025 – Addressing high food price inflation for food security and nutrition (Vol. 2025). Food & Agriculture Org.
<https://doi.org/10.4060/cd6008en>

Wu, B., Luo, S., Luo, H., Huang, H., Xu, F., Feng, S., & Xu, H. (2022). Improved phytoremediation of heavy metal contaminated soils by *Miscanthus floridulus* under a varied rhizosphere ecological characteristic. *Science of the Total Environment*, 808, 151995.

VVEU Conference Proceedings. (2026). *The role of entrepreneurial strategies in strengthening competitiveness and sustainability of agricultural enterprises in Croatia*. Book of Abstracts.

Xiang, N., Yao, Y., Yuen, J. S. K., Stout, A. J., Fennelly, C., Sylvia, R., Schnitzler, A., Wong, S., & Kaplan, D. L. (2022). Edible films for cultivated meat production. *Biomaterials*, 287, 121659.
<https://doi.org/10.1016/j.biomaterials.2022.121659>

You, L., Ros, G. H., Chen, Y., Shao, Q., Young, M. D., Zhang, F., & de Vries, W. (2023). Global mean nitrogen recovery efficiency in croplands can be enhanced by optimal nutrient, crop and soil management practices. *Nature Communications*, 14(1), 5747. <https://doi.org/10.1038/s41467-023-41504-2>

Zhang, G., Zhao, X., Li, X., Du, G., Zhou, J., & Chen, J. (2020). Challenges and possibilities for bio-manufacturing cultured meat. *Trends in Food Science & Technology*, 97, 443–450.
<https://doi.org/10.1016/j.tifs.2020.01.026>

Zhang, M., Tian, R., Tang, S., Wu, K., Wang, B., Liu, Y., Zhu, Y., Lu, H., & Liang, B. (2023). The structure and properties of lignin isolated from various lignocellulosic biomass by different treatment processes. *International Journal of Biological Macromolecules*, 243, 125219. <https://doi.org/10.1016/j.ijbiomac.2023.125219>

Zirman, A., Abed El-Nabi, M., Samuel, E., Anavy, L., Yakhini, Z., Nachman, I., & Rak, R. (2025). Pooled CRISPR screens identifies key regulators of bovine stem cell expansion for cultured meat. *Communications Biology*. <https://doi.org/10.1038/s42003-025-08760-y>



Co-funded by
the European Union



BIOSHIELD

Novel Biotechnological Solutions in Climate Change Mitigation

2024-1-EL01-KA220-HED-000251373

The European Commission's support to produce this publication does not constitute an endorsement of the contents, which reflect the views only of the authors, and the Commission cannot be held responsible for any use which may be made of the information contained therein. This curriculum content is licensed under

