Time to translate

A Roadmap For Photosynthesis To Drive Crop Improvement

European Strategic Research Agenda and Road Map to 2030

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A roadmap for Photosynthesis to drive crop improvement

This roadmap has been developed based on:

- Literature reviews.
- Results from four H2020 photosynthesis projects: CAPITALISE, Gain4Crops, PhotoBoost and BestCrop.
- Stakeholder opinions from online breeder and grower surveys (70 respondents)
- Two workshops to identify: (1) The needs of Industry and, (2) The barriers to translating academic research to crop breeders. This engaged 20 representatives from breeders, growers, vertical farmers, academics/EPSO representatives, consumers, crop genetic engineers, horticulturists, trade organisations, Euroseeds and the Plants for the Future Technology Platform.
- A Translational Photosynthesis workshop, co-organised by CAPITALISE and the French Groupment de Recherche. This brought together 50+ academics and industry representatives.
- Social Sciences Stakeholder Engagement with consumers, farmers and breeders.

This Roadmap has been developed by the CAPITALISE project (EC Grant Agreement 862201), with contributions from the GAIN4CROPS (ECGA 862087), PhotoBoost (ECGA 862127) and BestCrop (ECGA 101082091) projects and key stakeholders. This is a summary of the more detailed European Strategic Research Agenda and Road Map to 2030.
This document can be accessed using the QR code.

A call to action: the benefits of public private partnerships

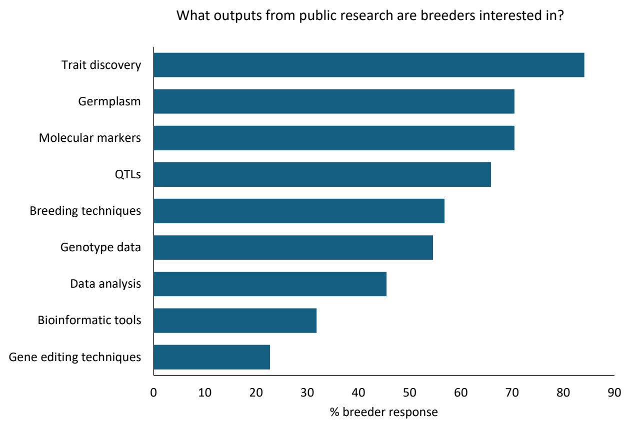
The European crop breeding sector consists of approximately 7000 businesses including numerous small to medium-sized enterprises (SMEs). The crop breeding sector plays a critical role in agricultural sustainability in Europe, and SMEs contribute significantly to the resilience of regional agriculture. These companies need to be innovative to remain competitive, but many lack significant research and innovation capacity. In contrast, larger companies have resources to invest in R&D but still benefit from collaborations with the public research base.

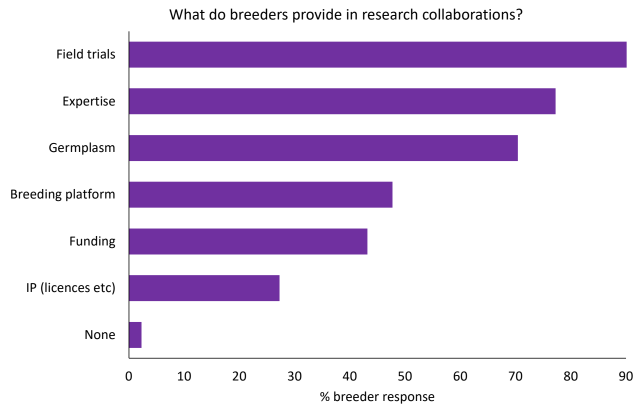
The current fragmented nature of research funding in plant and crop sciences is creating unnecessary barriers to rapid translation of promising results.

To strengthen European competitiveness in agriculture and the bioeconomy, an integrated strategy is needed to advance biotechnologies and accelerate crop research. Conventional crop development cycles of 10–15 years are mismatched with the 3–5 year research funding schemes. This limits opportunities to quickly reach high crop Technology Readiness Levels (TRL). A European approach can streamline the research-to-application pipeline, addressing inefficiencies and fragmentation that hamper responses to climate stresses, food security, and feedstock shortages.

While industry can support higher TRL innovations, short-term public funding often prioritises exploratory academic research and publications. This may discourage translation of results. Stronger collaboration between academia and industry is essential to advance promising strategies such as enhancing photosynthesis.

A survey of breeders highlighted specific research outputs desired from public research, and industry contributions to collaborations.





Declining public investment in crop research needs to be reversed

Reversing declining public investment in crop research and encouraging private funding through Public-Private Partnerships (PPPs) is critical for strategic collaborations in crop improvement. Despite EU commitments, the CAPITALISE project only identified 229 H2020 projects as relevant to "crop breeding" **with less than 0.5% of the €80 billion budget allocated to this research**. *Analysis by the Plants for the Future* ***European Technology Platform*** (ETP) revealed a decline in funding for plant breeding research, although Horizon Europe funds rose by 42% compared to FP7. Plants for the Future and others have already called for a new partnership "Optimising genetic potential for resilient and diverse production systems". This report confirms the need to harness discovery science and precompetitive breeding for improved crops and algal systems and accelerate promising areas including the multiple options to improve Photosynthesis discussed here.

KEY MESSAGES

Climate change is driving abiotic stresses that negatively impacts crop health and yields, reducing primary production and threatening food, feed and energy security. New climate resilient crops are urgently needed.

- ✔ Crop development is a long term investment taking 10-15 years and requiring a strategic approach. Time is of the essence. Research on relevant germplasm, improved genetic resources, tools, models and an innovative culture that embraces biotechnological advances are critical to accelerate the required improvements to crops.
- ✔ Public private partnership represent the best option to develop the tools and knowledge base to deliver a new generation of resilient sustainable climate adapted crops that address the emerging threats to primary production for food and the bioeconomy.
- ✔ Low level and declining public investment in crop breeding programmes needs to be reversed. Crop research needs a reinvigorated strategic programme, at the European level, to implement longer term (5+ years) well-funded (€8M+) collaborative research and innovation projects creating enabling environments to drive translational crop research.
- ✔ Photosynthesis is a complex process but has many underexploited traits with significant potential to improve crop yield and resilience to climate change. Recent scientific advances have demonstrated significant improvements in crop productivity through improving photosynthesis efficiency.
- ✔ Translation of Key Exploitable Results represents a priority research area. Collaborative working is needed between industry and the science base to overcome market failure in developing photosynthesis driven climate resilient crops.
- ✔ An enabling regulatory environment to support NGTs should be a short-term priority to accelerate the broader application of biotechnology. This will compliment conventional crop improvement pathways to develop some new plant varieties faster, and in a more precise manner to exploit promising traits and approaches.
- ✔ In parallel, environmental risk assessments should be undertaken, and literacy programmes developed and implemented, to educate citizens about NGTs and making informed risk assessments.
- ✔ Barriers to translating public research to industry need to be better understood and addressed. Life Cycle Analysis represents an important tool to address the socioeconomic costs, risks and benefits of the proposed approaches and will form a basis for commercial decision making. Issues regarding IP and the Nagoya protocol need to be resolved for maximal use of research outputs by Industry.

Society needs more resilient crops

There is an urgent need for improved climate resilient crops to mitigate the effects of abiotic stresses linked to a changing climate. Future food security to meet the needs of a growing global population and the shift to a biobased economy both require efficient sustainable agricultural production. To protect biodiversity, it is important that yields are increased to meet future demands without needing more land, leaving space for nature.

Addressing these challenges requires a combination of adaptation and mitigation strategies, technological innovation, and changes in agricultural practices to ensure food security and environmental sustainability. Future crops, irrespective of farming systems, need to respond effectively to multifactorial changes related to a changing climate and environment. A coherent, multifaceted approach is needed, supported by investment, cross sector collaborations and a supportive regulatory and policy environment that encompasses sustainability challenges and citizen concerns.

Four EU projects: CAPITALISE, Gain4Crops, PhotoBoost and BestCrop, have taken different approaches to improving the efficiency of photosynthesis in key European crops. Each project is making significant progress towards increasing the crop TRLs for breeders. This is not a simple task, significant barriers to translation exist.

This roadmap highlights how improved photosynthesis in crops is part of the solution. It explores the challenges faced by researchers and industry in taking research results to the grower and consumer, and highlights the potential future directions for photosynthesis research to meet breeder, grower and societal needs. This includes recommendations for strategic research and innovation approaches and timescales to inform key actors in the value chain, policy makers, and public/private sector actors and funders.

Plant breeding is reliant on introducing genetic diversity to improve crop characteristics. This can be achieved by Conventional Breeding or New Genomic Techniques.

Modern Conventional Plant Breeding is a high-tech selective process involving phenotyping, genotyping, molecular markers, and genomic selection. It expands the gene pool over multiple generations but is time-consuming (10-15 years) and lacks precision, as undesirable traits can be inherited with target traits.

New Genomic Techniques (NGTs) like CRISPR-Cas9 and synthetic biology enable precise gene editing to enhance traits such as drought tolerance or disease resistance, without unwanted traits. NGTs are faster (1-5 years), more sustainable, and can overcome barriers to gene flow that limit conventional breeding.

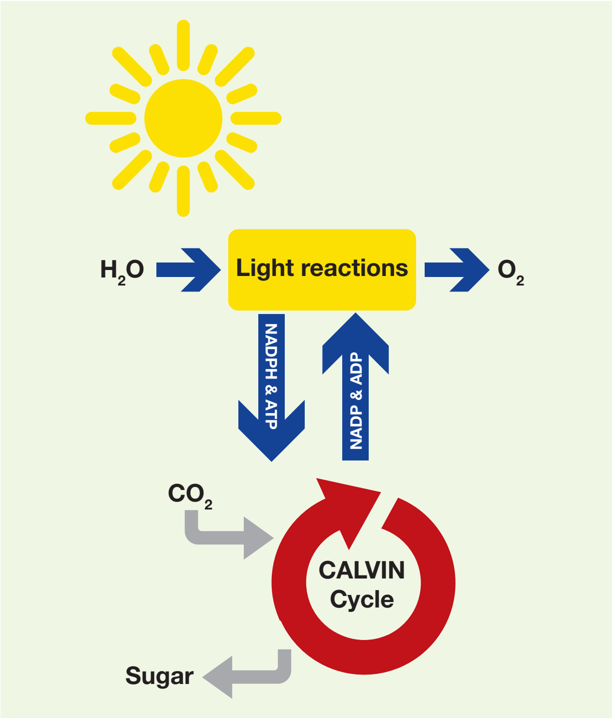
Photosynthesis driving crops of the future

Photosynthesis is a fundamental process that drives plant growth and productivity by converting light energy into chemical energy. In the context of plant breeding, scientific advances have shown photosynthesis-related traits have significant potential to enhance crop yields and resilience in the face of increasing abiotic stresses linked to climate change.

While photosynthesis is a promising science driven approach and has attracted the interest of commercial breeders, it has not gained traction in breeding programmes in part due to complexity and difficulties for selection that require better tools.

The complexity that has prevented exploitation in the past is increasingly well understood and is now opening up multiple promising crop improvements. This includes options to combine and stack traits in plants to address different abiotic stresses that reflect changing real world environments.

Improving photosynthesis is one of the most promising options to improve crop yields and achieve global food security

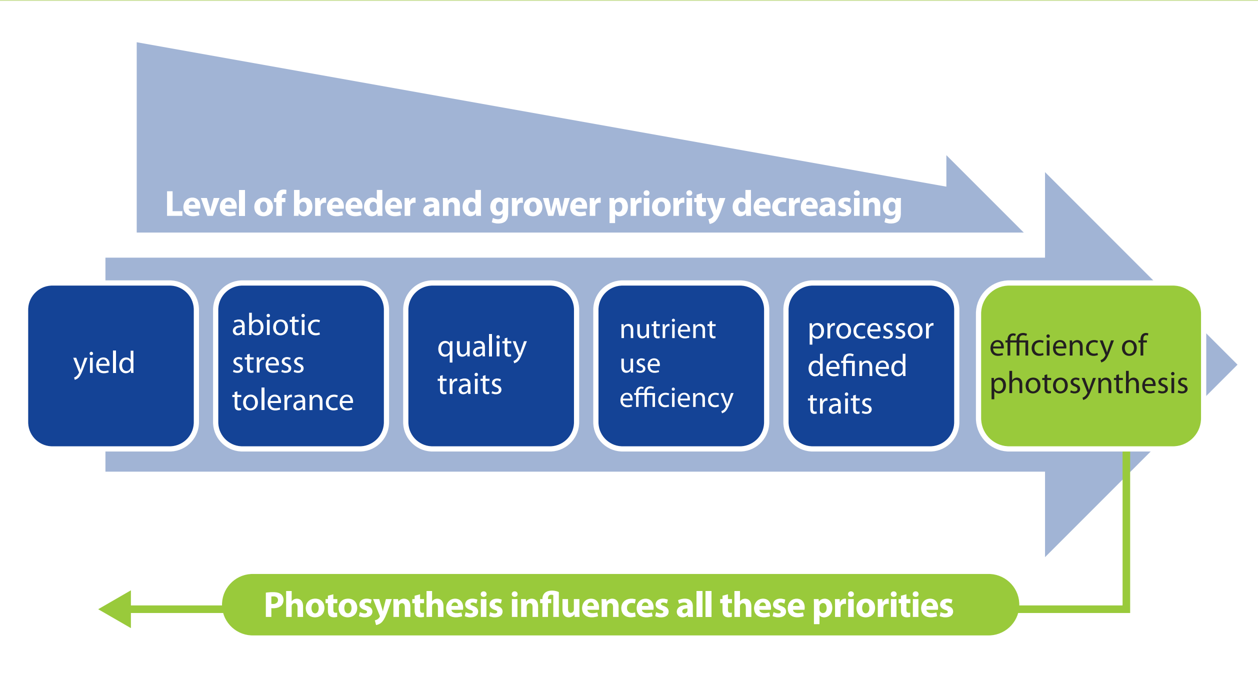


Over 50 years of research is providing exciting new approaches for climate-smart crop breeding. Timely translation is needed to deliver food and energy security, and to provide plant derived biomaterials, and climate change mitigation. Despite these advances, developing new resilient high-yielding varieties typically still takes 10-15 years. Given the increasing pressure on agricultural systems, speed is of the essence.

To accelerate the translation of photosynthesis requires investment and cross sector interdisciplinary working. Strategic initiatives are needed in the short term through Public Private Partnerships to transfer the knowledge from academic plant sciences to the crop breeding sector.

Photosynthesis: an undervalued solution?

A CAPITALISE survey asked seventy breeders and growers to prioritise their current breeding goals for their crops of interest. Overall, the three highest priorities identified across all the crops were yield, abiotic stress tolerance and quality traits, by both breeders and growers. This figure represents an overview of these results.



Efficiency of photosynthesis was rated a relatively low priority. The breeders and growers surveyed did not seem to recognise that improved photosynthetic efficiency has been shown to influence their other priorities.

To date, policy drivers for EC investment in photosynthesis research were primarily linked to population growth, increasing yield and long-term food security. Unsurprisingly, industry breeding goals and grower crop priorities were focussed on more immediate economic challenges linked to abiotic stresses associated with climate change and market demands.

The full advantages of improving photosynthetic efficiency are not fully appreciated by many value chain actors

Dramatic crop improvements achieved by exploiting photosynthesis

Quantifying the benefits of improved photosynthesis to crop yield has been difficult to demonstrate. Recent advances in genomics, high-throughput phenotyping, and modelling now enable scientists to demonstrate the yield benefits of improved photosynthetic efficiency in genetically modified plants through lab and field trials.

Barley	Chlorophyl tuning: A pale green barley line showed a 40-50% reduction in transpiration rate under drought stress and 40% increased photosynthetic efficiency under high light conditions (BestCrop).[1]
Potato	Expression of a glycolate dehydrogenase polyprotein (DEFp) led to 12-45% increases in potato tuber yield (PhotoBoost).[2]
	Introduction of algal carbon concentration mechanism components into potato chloroplast led to 17-42% enhanced tuber yield (PhotoBoost).[3]
	Integration of a novel oxygen scavenging pathway showed 25-31% enhanced yield and increased photosynthesis related metabolites (PhotoBoost).[3]
Soybean	Accelerating plant recovery from photoprotection delivered a 33% improvement in seed yield.[4]
Rice	The overexpression of a transcription factor that regulates photosynthetic capacity led to a 41-68% yield increase.[5]
	Overexpressing Rubisco in rice enhanced yields by 17-28%.[6]

[1]Persello et al., 2024, Plant Cell Rep, 43, 246; [2]Nölke & Schillberg, 2020, In: Climate Change, Photosynthesis and Advanced Biofuels. http://link.springer.com/10.1007/978-981-15-5228-1_5; [3] Unpublished PhotoBoost project; [4]De Souza et al. (2022), Science, 377, 851–854. [5]Wei et al. (2022), Science, 377, eabi8455; [6]Yoon et al. (2020), Nat Food, 1, 134–139.

Integrating photosynthesis into crop improvements

Multiple processes are coupled to photosynthesis from the cellular to the canopy scale. A plethora of other factors, including water, nutrients, pathogens, temperature, light, and management practices affect photosynthesis and co-limit yield. An integrative research approach is essential to understand and exploit photosynthesis within a complex agroecological context for improving yield and resilience.

Selected features of such an integrative photosynthesis research programme are outlined below:

- ✔ ***A whole-plant perspective:*** Research should consider photosynthetic traits in the context of the whole plant, including its non-photosynthetic parts such as roots, and the plant holobiont, i.e. the plant and its associated microbiome.
- ✔ ***A product-centric perspective:*** Prioritizing desired qualities like mineral nutrient or protein content, ease of processing, and addressing diverse value chains (food and non-food applications) may require distinct strategies tailored to optimize product quality.
- ✔ ***A climate-centric perspective:*** This will require expanding the pool of genetic variation available for breeding from landraces, crop wild relatives, in addition to novel variants through new breeding technologies and chromosome engineering.
- ✔ ***Photosynthesis in the context of different cropping systems:*** Optimal photosynthetic traits will vary for different cropping systems and may need to be adapted to new cropping schemes, including multi-cropping and other agroecological types of farming, or for combining crop production with renewable energy production (agrophotovoltaics). Indoor agriculture under constant, controlled environments eliminates the need for adaptive photosynthetic traits, allowing for higher conversion efficiencies. Novel photosynthetic ideotypes will be required to fully exploit the potential benefits of these alternative growing systems.
- ✔ ***Photosynthesis in multi-purpose crops:*** Different qualities are needed to provide cost-efficient food, fibre and renewable resources. Crops can also be modified to better provide important ecosystem services and contribute to climate change mitigation, e.g. Carbon Farming.
- ✔ ***Integrative research requires a Multi-Actor Approach:*** Collaboration with breeders and growers will identify key knowledge gaps, while participatory research will enhance field trial design and analysis. This integrated approach aims to accelerate the development of novel germplasm, benefiting farmers and consumers, and effectively disseminating findings.

Contribution to EU policy

This Roadmap aligns with the **Green Deal** and **Farm to Fork** priorities, focusing on crop breeding to enhance photosynthesis for higher yields with lower inputs, supporting sustainable farming and the Common Agricultural Policy (CAP) goals. The ambition is to deliver sustainable production within planetary boundaries, contributing to food security, climate action, and multiple **Sustainable Development Goals** (2, 3, 6, 7, 12, 13, 15). Biotechnologies are key to accelerating progress supporting conventional and new breeding techniques. This strategy will benefit from the proposed EU Biotech Law and improved regulatory environments.

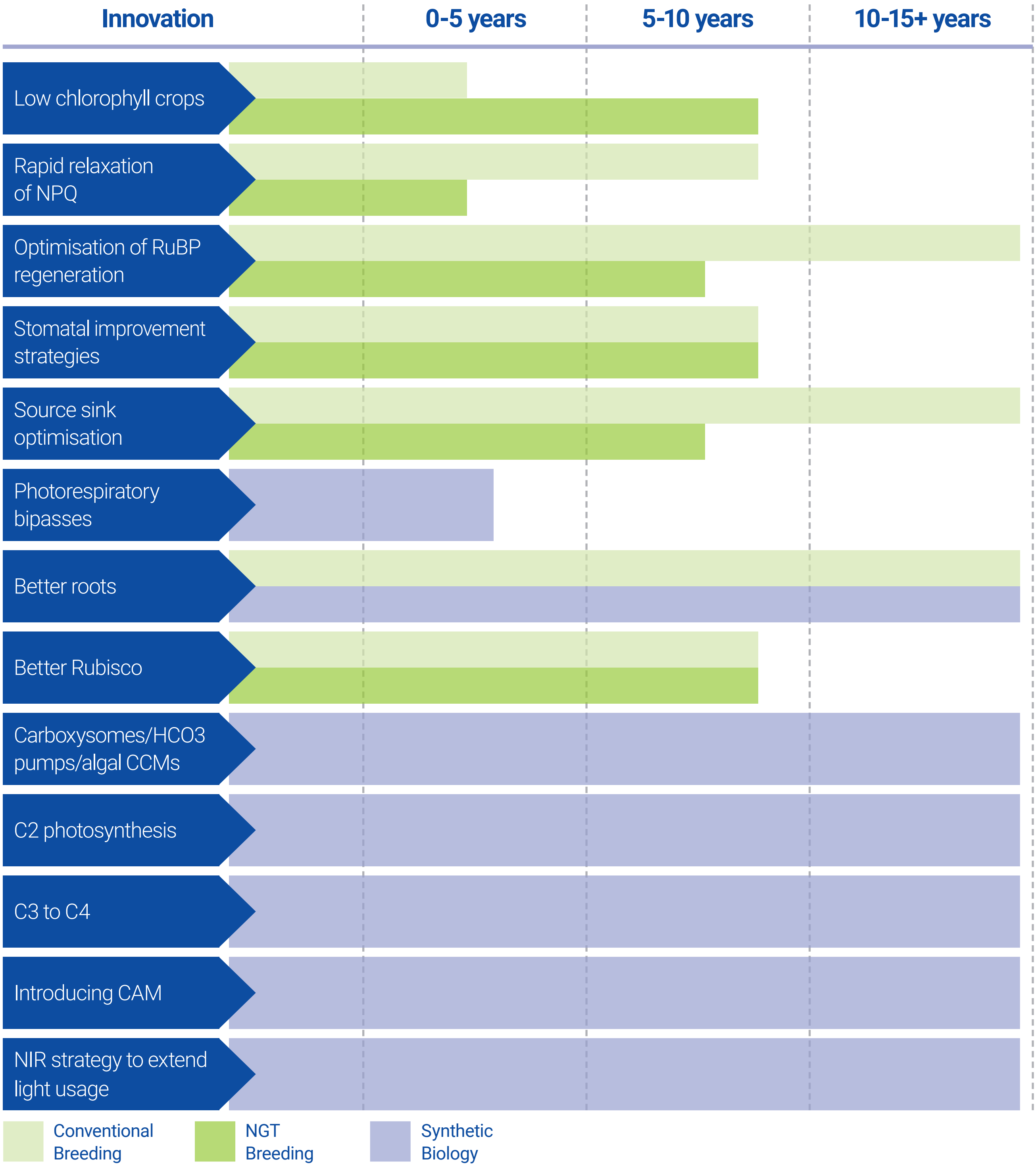
Stakeholder dialogues have emphasized the need for investment in innovation and knowledge-sharing to maintain crop yields under challenging conditions. Enhancing photosynthesis aligns with the Strategic Dialogue on the Future of EU Agriculture recommendations, promoting better farmland management, water-resilient agriculture, and innovative breeding. This approach boosts productivity without expanding farmland, supporting the Biodiversity 2030 strategy by protecting natural spaces. It also reduces fertilizer use and improves water use efficiency.

New bioeconomy optimised crops will strengthen the bioeconomy and meet predicted expansion by delivering cost-effective products for diverse uses including food, bioenergy, and biomaterials. This future proofed sustainable primary production will support the EU's Green Transition and circular economy goals, as outlined in the European Bioeconomy Strategy (2018).

Photosynthesis Improvement Strategies

There are a number of well-known strategies for improvement of photosynthesis efficiency, at various levels of advancement and translation level, many of which are used in CAPITALISE, GAIN4CROPS, PhotoBoost and BestCrop. Each strategy presents different challenges and benefits, and suit particular environments and type of agriculture. No single strategy is applicable to all crops, but combinations of some strategies may give wide ranging benefits to crop resilience and efficiency. Modelling can give insights into the most optimal combinations.

Timeline for strategies to reach crop TRL7



CTRL	Definition	
TRL1	Basic principles for improving target crop(s) identified	**Preliminary evaluation**
TRL 2	Crop improvement concept formulated	
TRL 3	Experimental proof of concept (laboratory level)	**Experimental testing**
TRL 4	Improvement validated in a crop model (laboratory level)	
TRL 5	Improvement validated in a field/glass house environment	**Pre-commercial assessments**
TRL 6	Pre-breeding with improved traits in a relevant environment	
TRL 7	Improved prebreeding crop line demonstration in a grower/farm environment	**Commercial Deployment**
TRL 8	Breeding in elite crop line achieved and qualified	
TRL 9	Elite crop line incorporating trait(s) proven in commercial growing environments	

1 Lower Chlorophyll crops

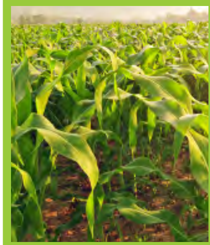
Crop TRL 5-6

Decreasing the chlorophyll concentration at the top of a crop allows more light to reach the lower canopy, boosting overall plant photosynthetic efficiency. Since chlorophyll complexes are nitrogen rich, better nitrogen use efficiency is achieved. Natural variation has been identified for this trait.

PYI	20%	Timeline for Translation	2-5 years	Benefits
Challenges Improved field instrumentation, robust model predictions. Stacking with other strategies.				N_2

2 Rapid Relaxation of NPQ

Crop TRL 6

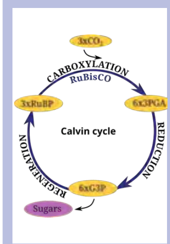


Light intensity can be quite changeable within crop canopies. Sharp fluctuations due to wind movement, overtopping leaves and changing solar angles, lead to less efficient photosynthesis. This strategy looks at minimizing loss of photosynthetic efficiency when leaves are exposed to changes in light intensity. Natural variation has been identified.

PYI	10-20%	Timeline for Translation 5-10 conventional breeding, 0-5 NGTs	Benefits
Challenges - Low-cost sensors for phenotyping needed. Crop models. Understanding NPQ regulation under different environmental conditions.			

3 Optimisation of regulation of Calvin cycle and Electron Transport Chain

Crop TRL 5



The Calvin cycle is the primary photosynthetic pathway for assimilation of atmospheric CO_2 in the majority of C3 crops. Manipulating the expression of key enzymes in this cycle and the photosynthetic electron transport chain (ETC) has been shown to enhance photosynthesis and growth.

PYI	Up to 70%	Timeline for Translation	5-10 years NGT, 10+ Conventional breeding

Challenges

Remote sensing systems for selection in the field needed. Acceptance of NBTs.

Benefits

4 Better Rubisco

Crop TRL 1-4

Rubisco activity is highly regulated and coordinated in tandem with other photosynthetic reactions and plant processes. Rubisco is a very inefficient enzyme, its abundance, catalytic properties and regulation of activity are all targets for improvement. Natural variation has been identified for some Rubisco traits. GE is needed for many manipulations.

PYI	60%	Timeline for Translation	5-10 years

Challenges

Predictive modelling, computational and AI tools needed. Acceptance of GM technologies.

Benefits

N_2

5 Adding cyano carboxysomes, HCO3 pumps algal CCMs

CROP TRL 1-2

Introducing carbon concentrating mechanisms (CCMs) into C3 crops is a high-risk, high-reward strategy to boost yields and resilience. CCMs concentrate CO_2 around Rubisco, reducing photorespiration and favouring CO_2 assimilation to boost yield.

PYI	up to 60%	Timeline for Translation	10-15 years

Challenges

Specific expression and accumulation of CCM-related proteins, correct assembly and functionality of protein complexes. Acceptance of GM technologies.

Benefits

CSeq

6 NIR strategy to extend light usage

Crop TRL 2

Green plants absorb light energy in a limited range (400-700nm). Extending the ability of plant pigments to absorb energy from a wider range of the spectrum to 750nm into the far red range can increase light absorption by 20%.

PYI	20%	Timeline for Translation	10-15 years	Benefits
Challenges Challenges - Modelling to predict far red light dependent gene expression in plants. Cellular models. Acceptance of GM technologies.				

7 Stomatal strategies

Crop TRL 2-5

Stomata, are small pores on the surfaces of leaves. The behaviour of stomata determines CO_2 uptake for photosynthesis and water loss through transpiration. There are numerous targets that can be exploited in crops to manipulate stomatal behaviour such as their density, sensitivity and speed of response.

PYI	20%	Timeline for Translation 3-5 years for density, 5-10 years for rapidity	Benefits
Challenges - Identification of the key genes involved. Development of tools for deep phenotyping.			CSeq

8 Synthetic Photorespiratory Bipasses

Crop TRL 4-6

Synthetic Photorespiratory Bypasses circumvent natural photorespiration, a wasteful process involving the loss of 25% of the previously assimilated carbon as CO_2. Photorespiratory bypasses have been extensively developed in Europe and been demonstrated in field trials to significantly increase yield, biomass and grain quality in crops.

PYI	30-50%	Timeline for Translation 0-5 years	Benefits
Challenges - Regulatory approval and acceptance of GM technologies			

9 C3 to C4

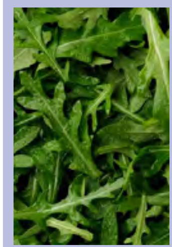
Crop TRL 2-3

C_4 plants employ a biochemical carbon pump that elevates the concentration of CO_2 available to Rubisco, achieving around 50% higher energy conversion efficiency compared to C3 plants. Converting C3 crops to utilize C4 photosynthesis would significantly enhances crop productivity.

PYI	50%	Timeline for Translation 10-15 years	Benefits
Challenges - The genetic blueprint for C_4 photosynthesis. Introduction of multiple transgenes - scientifically and technically highly challenging. Regulatory approval and acceptance of GM technologies.			

10 C2 Photosynthesis

Crop TRL 3



C2 photosynthesis is a simple carbon concentrating mechanism (CCM) that recycles CO_2 released from photorespiration. This has only been identified in Rocket. This natural CO_2 recycling mechanism allows C_2 plants to avoid the significant carbon costs of photorespiration, to ultimately improve carbon-, water-, and nitrogen - use efficiency compared to C_3 close relatives.

PYI	>20%	Timeline for Translation	10-15 years

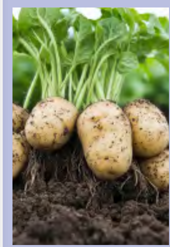
Challenges

Predictive modelling, computational and AI tools needed. Acceptance of GM technologies.

Benefits

11 Source Sink interactions

Crop TRL 3-4



Sinks are the rapidly growing parts of the plant that receive sugars and other compounds from the source, the green photosynthesizing leaves and shoots. Reducing, sink limitations; and better timing and control of source – sink activities help to maximise photosynthetic source production and yield.

PYI	30-50%	Timeline for Translation	5-15 years

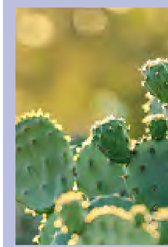
Challenges

Assays to identify sink limitation, better tools for measuring transport limitation in the phloem. Assays for screening in the field.

Benefits

12 Integrating CAM

Crop TRL 2



CAM plants are incredibly water use efficient because they capture CO_2 at night, rather than during the day like C3 and C4 plants. Introducing drought inducible CAM in to C3 plants will significantly reduce transpiration and improve WUE in water stressed conditions.

PYI	yield maintained under drought stress	Timeline for Translation	10-15 years

Challenges

Improved modelling. CAM gene expression and regulation. Significant anatomical changes needed. Low cold tolerance

Benefits

13 Better Roots

Crop TRL 2-3

Rhizospheric interactions are a key component of crop performance needed to support improved photosynthesis. Better roots support all other improvement strategies.

PYI	to maintain rather than raise yield	Timeline for Translation	10-15 years	Benefits

Challenges

A complex trait, difficult to phenotype in the field.

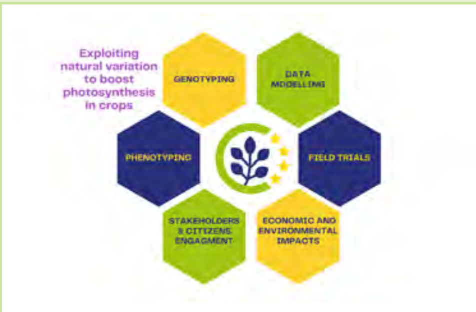
INDEX KEY

Increase in Yield	Synthetic biology
Water Use Efficiency	New Genomic Techniques
Carbon Sequestation	Conventional breeding
Nitrogen use efficiency	PYI Potential yield increase expected

Gain4Crops PhotoBoost BestCrop CAPITALISE

Four projects with four approaches to exploiting Photosynthesis

The EC recently invested €27M into four early-stage projects exploring different promising approaches to improve crop photosynthesis and increase yield and crop quality. This strategic approach has advanced the science to early field trials. CAPITALISE, PhotoBoost, GAIN4CROPS and BestCrop present different approaches to improving the efficiency of photosynthesis in a range of different crops using a variety of promising strategies.



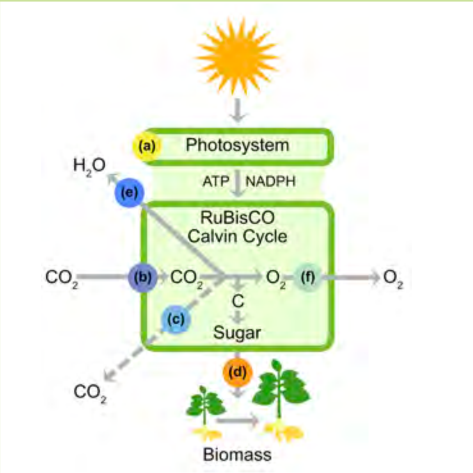
The CAPITALISE project is exploiting natural variation in core elements of photosynthesis in diverse collections of Barley, Maize and Tomato, to identify and develop new genetic resources, models and support tools. By using a conventional modern breeding approach, the majority of CAPITALISE outputs can be used directly in the EC without regulation.

Using a highly multidisciplinary approach CAPITALISE is advancing the following most promising strategies:

i) Tuning the Calvin Cycle (CC) via a) Rubisco activity and activation state & b) activity of the RuBP regeneration phase of CC. ii) Kinetics of photosynthetic responses to changes in irradiance a) kinetics of build-up of CC after an irradiance increase; b) activation of Rubisco after an irradiance increase & c) deactivation of qE component of non photochemical quenching after an irradiance decrease. iii) Tuning leaf chlorophyll via a) Photosystem II antenna size & b) Photosystems density.

The **GAIN4CROPS** project aims to increase photosynthetic energy conversion efficiency using a complementary approach that combines natural variation in photosynthetic carbon assimilation strategies with new-to-nature approaches to overcome photorespiration, the main limitation of energy conversion efficiency in C3 plants, and replace it with a carbon-neutral or carbon-fixing synthetic bypass.

The approach is using high-precision genome editing and extensive interspecific crosses between phylogenetically related C3 crops and their wild C3-C4 intermediate relatives in Sunflower. This is expanding the access to genetic variation beyond the species borders. In a parallel, complementary approach, GAIN4CROPS is designing nature-inspired synthetic versions of C3-C4 intermediates that require fewer genes for implementation, and developing novel pathway designs that are more efficient than naturally occurring variations in photosynthetic carbon assimilation.



The **PhotoBoost** approach involves six new and improved strategies that have been exploited to boost photosynthetic efficiency by at least 30% and biomass yields by at least 40%.

PhotoBoost has met their goal by developing enhanced C3 crops (Potato and Rice) that combine one or more of the following strategies: (a) the optimisation of light reactions during photosynthesis; (b) the integration of an algal CCM; (c) the introduction of an engineered photorespiratory bypass mechanism; (d) the optimisation of source–sink capacity (only in potato); and (e) the adaptation of stomatal conductance by the introduction of a hexokinase gene, to improve water-use efficiency. PhotoBoost have also explored the integration of an oxygen scavenging mechanism as a novel strategy (f) to further reduce photorespiration and boost the efficiency of photosynthesis.

The **BestCrop** project adopts the most promising strategies to improve the photosynthetic properties and ozone assimilation capacity of barley by:

i) Tuning leaf chlorophyll content and modifying canopy architecture; ii) Increasing the kinetics of photosynthetic responses to changes in irradiance; iii) Introducing photorespiration bypasses; iv) Modulating stomatal opening, thus increasing the rate of carbon dioxide fixation and ozone assimilation.

In parallel, the resulting barley straw is tailored to: i) increase straw protein content to make it suitable for the development of alternative biolubricants and feed sources; ii) control cellulose/lignin contents and lignin properties to develop straw-based construction panels and polymer composites.

Strategic Research Agenda priority areas

SRA Priority 1: Phenotyping and Validation

Identification of genomic control coefficients

- ✔ Validation of naturally derived innovations with transgenic/genome-edited lines with modified expression of traits underlying genetic determinants. This will explore the genomic basis for established variation in selected traits and the potential for enhancing a trait by altered gene expression in situ e.g. modifying a promotor. The aim is to rapidly establish genomic control coefficients for key physiological pathways. Identification of key genes is the first step i.e. genes underpinning natural variation for a trait.

Identification of diagnostic signatures

- ✔ Identification of novel diagnostic signatures for combinations of traits which improve photosynthetic performance and yield.
- ✔ Ongoing phenotyping to feed back into QTL and GWAS mapping, integrating trait data to allow finer characterisation / confirmation of loci discovered in previous mapping rounds.

SRA Priority 2: Translation of QTL/QTN

Validation in inbred backgrounds

- ✔ Survey elite germplasm (ex PVP)/breeding material, for allele/haplotype variation in candidate genes/QTLs (ideally validated genes) that affect selected traits previously detected as QTLs.
- ✔ Near Isogenic lines (NILs) or similar (e.g. overexpressor of trait gene) in relevant parents.
- ✔ Characterise performance of selected traits in prebreeding and elite lines in controlled & field conditions.

Fine-mapping / candidate gene identification

- ✔ New recombination in offspring
- ✔ Genome editing
- ✔ Physiological characterisation

Facilitate implementation in breeding

- ✔ Develop diagnostic markers

Genomic selection

- ✔ Exploiting advanced understanding of the genetic make-up of crop plants and measurable photosynthesis traits to increase genetic gain of (complex) target traits. Molecular markers will be a key tool to reduce time and costs.
- ✔ Activities based on the recognition that a trait maybe under multi-locus control for which improvement by genomic selection may be necessary.

Building on Project' Key Exploitable Results (KERs) the following "next steps" represent a Strategic Research Agenda (SRA) to speed up the translation of promising photosynthesis strategies towards the breeding sector. Implementing this SRA will require cross sector strategic efforts through Public Private Partnerships (PPP) to develop new collaborations. This should build interdisciplinary synergies, exploit efficiencies of scale, and accelerate research and innovation pathways.

Additional funding from public and private sources including industry, philanthropy, Horizon Europe and follow-on European programmes will be critical to facilitate future crop improvements. This includes exploiting advances in photosynthesis science.

SRA Priority 3: Model-development and improvement

Model-development

- ✔ Use of existing, and generation of new datasets to identify the genetic architecture of plasticity in photosynthetic efficiency and its genetic correlation to growth.
- ✔ Dynamics of fluxes in photosynthesis-related pathways: this will call for new ways for flux profiling and can be used to specify missing regulators.
- ✔ Integration into i) canopy models and ii) crop models.

Model improvement cycle

- ✔ Use models to identify key regulatory steps as a function of relevant environmental conditions.
  i) Genotype to phenotype: Find sequence variation in genes involved in key steps/traits and phenotype corresponding plant material (diversity panels, breeding material).
  ii) Phenotype to genotype: Phenotype variation in critical steps/traits across diversity panels and breeding material and correlate with sequence variation.
- ✔ Feed results into the model-improvement and start the next cycle.

SRA priority 4: Genomic toolbox/Tuning the CBC - using transgenic/ non-transgenic approaches

Advance emerging alternative strategies to provide novel approaches to modify target genes known from transgenic work to improve photosynthesis:

- ✔ Newly identified twelve base pair palindromic sequence from the octopine synthase gene can be used to upregulate multiple genes simultaneously (cis-genic).
- ✔ Deletion of upstream open reading frames with stop codons, this would offer a non-GM approach. Targets are easy to identify and multiple genes can be targeted simultaneously.

SRA Priority 5: Chlorophyll Tuning

- ✔ Demonstrate improved yield and/or increased efficiency in water and nitrogen use.
- ✔ Investigate the potential of increased albedo to mitigate climate change and to increase the efficiency of bifacial photovoltaic systems.
- ✔ Identify novel strategies that allow a chlorophyll gradient concentration through the canopy.
- ✔ Investigate the potential of "staygreen" phenotypes, i.e. delayed senescence on crop yield.
- ✔ Use of new phenotyping tools to quantitatively assess variation and performance.
- ✔ Application of gene editing or conventional breeding to transfer to elite lines.

SRA Priority 6: Into the Field-Crop Performance to advance improvement strategies and deliver data to support Life Cycle Analysis, Socio-economic and Environmental assessments

- ✔ Demonstrate a yield increase of the photosynthetically optimized plants (prebreeding and elite lines) for target crops.
- ✔ Assessment of the inputs required to achieve target crop performance (>10%): fertilizer and/or irrigation vs standard lines.
- ✔ Assess the susceptibility of photosynthetically improved crop varieties to biotic/abiotic stresses vs standard lines.
- ✔ Assess impacts on the soil microbiome of roots e.g. impact of increased root exudates or below ground root biomass and necromass.
- ✔ Assess the impact of the soil microbiome and root properties on above ground photosynthetic activity.
- ✔ Determine the characteristics of the optimized lines for end use e.g., harvest/ processing and identify desirable traits to improve.
- ✔ Assess the suitability of improved varieties for different (changing) environments and farming practices.
- ✔ Acceptability to CITIZENS = CONSUMERS evaluated across different European regions and demographics.
- ✔ Explore the possibilities for stacking of traits.

SRA Priority 7: Phenotyping Tool Development

- ✔ Awareness raising and training about new agile and high throughput phenotyping tools.
- ✔ Exploitation of the chlorophyll a/b ratio non-destructive analysis devices developed by CEA and PSI for use by breeders and growers and researchers in field environments.
- ✔ Improved tools suitable for assessing target traits in field trials and crop breeding programmes.
- ✔ Development of 'breeders eye' tool for assessment of crop health for breeders and grower use in crop breeding and crop management strategies. This is expected to utilise photosynthesis traits as measures of crop health and performance.

SRA Priorities 8: Synthetic Biology approaches

- ✔ Transfer successful synthetic biology strategies (e.g. developed and demonstrated by PhotoBoost) to other food and feed crops.
- ✔ Perform further field trials to confirm robustness and sustainability of generated plant lines showing improved photosynthesis and biomass yield.
- ✔ Perform studies to investigate nutritional value and processing of generated plant lines showing improved photosynthesis and biomass yield.
- ✔ Test further stacking strategies and alternative synthetic biology approaches.
- ✔ Develop an evidence base to support regulatory approval and market adoption of suitable tools and approaches.

Short Term Topic suggestions for Horizon Europe Cluster 6

Building on recent progress in EU projects, follow-on funding in future Cluster 6 work programmes is recommended to advance promising results. Proposed 2026-2027 topics align with the CropBooster Roadmap (CropBooster-P, Grant 817690) and the EPSO Working Group Photosynthesis, Abiotic Stress, Input Use Efficiency.Budgets should build on the earlier calls to reflect costs of inflation.

Photosynthetic resilience of crops in a changing climate (RIA TRL2-4)

Photosynthesis and its connection with plant development, yield, source/sink dynamics and respiration should be key considerations of plant breeding. This needs to be carried out in increasingly challenging field conditions with multiple limitations. This calls for the development of a selection of genetic variants associated with enhanced photosynthetic performance using fine-mapping, validating these variants in elite inbred and heterotic backgrounds and developing diagnostic markers. Use of model-guided germplasm improvement should simultaneously enhance model performance and speed up the development of improved accessions.

1. Non-destructive phenotyping of photosynthesis in response to stress (RIA TRL3-6)

The precision of phenotyping remains a limiting factor in genetic selection approaches. The development of genetic strategies to identify genes of interest, along with the description of increasingly detailed traits, requires the development of non-destructive phenotyping tools with higher resolution. Instrumentation and analysis methods must be developed to achieve quantitative and contextualised measurements for phenotyping of photosynthetic efficiency in plants whether in controlled and instrumented environments or in the field. Additionally, tools for data acquisition, storage, access, and modelling are needed. These spatio-temporal studies are crucial for providing data for model design and plant ideotype research.

2. Improved nitrogen fixation for increased photosynthetic CO_2 assimilation (RIA TRL3-6)

To sustainably enhance agricultural productivity, it is important to improve both photosynthesis and nitrogen fixation. This approach would boost the productivity of existing nitrogen-fixing crops by providing them with more energy for nitrogen fixation and more carbon for root biomass alongside and more carbon for above ground growth and more nitrogen for photosynthesis. By leveraging increases in nitrogen fixation and photosynthesis, we can establish a foundation for high-yielding and sustainable agriculture.

3. Redesigning photosynthesis for crops of the future (RIA TRL4-6)

Recent advances in protein engineering allow the design of new-to-nature enzyme activities that outperform existing enzymes in terms of kinetic properties, selectivity and, when combined into novel metabolic pathways, substrate conversion efficiency. The transfer of new-to-nature and/or new-to-crop pathways into crops enables step changes in photosynthetic carbon conversion efficiency, as well as water and nitrogen use efficiency, that are unlikely to be achievable through canonical breeding approaches. A research programme aimed at achieving sustainable crop improvement should be accompanied by a research theme that addresses the inherent limitations of conventional crop breeding.

Key enabling technologies: tools to support translation

Recent innovations and emerging technologies are transforming plant science and crop breeding. Key enabling technologies include lab-based phenotyping devices; high throughput devices for screening in laboratory/indoor growth facilities; field devices for researchers and breeders to rapidly screen traits; and large-scale deployable sensors and satellite imaging.

Science and technology discussions at two CAPITALISE Workshops focussed on predicting the current and future trends shaping plant breeding, and highlighting innovations needed to accelerate the translation of results from lab to field. The main insights are summarized below.

Innovations/Technologies	Reasoning
GE and precision breeding	Essential to speed up the breeding process enabling incorporation of improved traits to crops in response to rapidly changing climatic conditions.
Synthetic biology for whole pathway development	An active research area enabled through gene editing. Examples include rewiring photorespiration (GAIN4CROPS and BestCrop) as well as the use of plant systems as cell factories.
Expanding the genetic diversity of crops	Allelic diversity in modern crops has been severely reduced during the selection process. Genetic diversification of crops can be improved by exploiting crop genetic resource collections to mine for improved stress resilience, adaptivity and productivity traits.
Improved multi-trait breeding approaches required	Conventional or NGT breeding methods to achieve resilience to multiple (but potentially short term) stresses associated with climate change to improve yield, resiliencies and resource use efficiencies, that will enable photosynthetic improvements to be 'expressed' under wide agro-ecological scenarios.
Life Cycle Analysis	To quantify the real cost-benefits of the adoption of agronomic innovations promoting better decision making for investment.
"On-farm" living labs to advance from controlled environments to field phenotyping	There is an urgent need to facilitate the rapid translation of research towards breeding programmes. Field phenotyping is a vital step to validate outputs and progress crop TRLs. Suitable sites, including "on-farm" living labs are needed to allow for testing under real world and experimental conditions.
Sensors, digitisation, AI data platforms and Envirotyping	Rapidly emerging technologies in agriculture will enable better field phenotyping, as well as improved mechanisation and robotics in plant breeding and farming practices. Plant breeding is increasingly 'big data driven' and innovations in AI and modelling are providing tools to collect, process and analyse large data sets. Better and cheaper sensors will allow 'Envirotyping' i.e. the use of environmental factors eg. soil, climate, local ecology to compliment genotyping and phenotyping to improve crop modelling, phenotype predictions and management practices.

The need for better phenotyping towards field-based photosynthesis

Advances in tools and technologies are now enabling the identification, quantification, and application of photosynthesis traits in field-based breeding programs. The tools currently used by researchers are not always user friendly enough to be embraced by breeders and growers. Scaling up effective translation to the field requires new breeder-friendly phenotyping tools using standardized tools & methods to measure photosynthesis. This will complement the expertise of breeders, facilitating faster adoption of scientific advances.

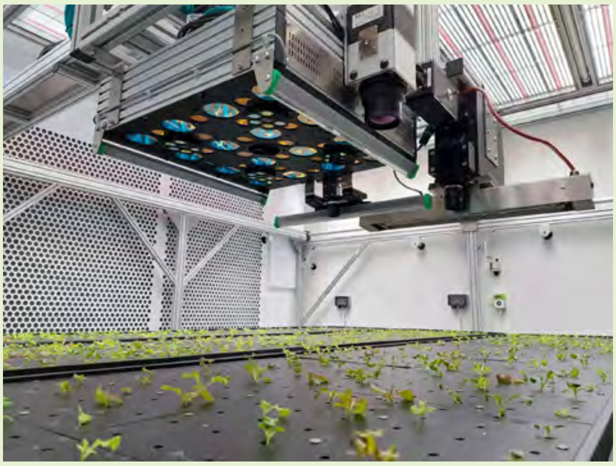
Credit PSI

A photosynthesis based accelerated breeding toolbox for next generation crop resilience breeding programmes.

Rapid phenotyping of photosynthesis in the field is critical to understand the limits to crop performance under changing environmental conditions. Easy-to-use sensor arrays for rapid phenotyping are integrated with advanced predictive modelling. This quantitative "Breeders Fitness Eye 2.0" is a new approach for breeders to access the wealth of information on plant performance.

High-throughput phenotyping infrastructures are becoming available in crop research institutes across Europe. This expands the scale and robustness of experimental work. The new NPEC system at Wageningen allows high-throughput phenotyping to assess plant performance. At IPK, the recently installed Phenosphere represents an advanced indoor high-throughput phenotyping system using strictly controlled environmental conditions to run climate simulations. These systems represent a new level of indoor phenotyping to accelerate translation of research.

The PhenoSphere at IPK - Credit IPK



NPEC at Wageningen - Credit WUR

Ground robotics and state of the art field phenotyping

Field phenotyping using manual methods is labor-intensive and inefficient. Advanced field phenotyping systems are increasingly vital, enabling the collection of extensive data to support analysis and decision-making. At the CAPITALISE workshop in France, the PhenoMobile at Arvalis showcased high-throughput field phenotyping capabilities. This fully automated, ultra-precise system continuously monitors multiple crop traits non-destructively in field conditions. The integration of AI and robotics is anticipated to play a growing role in advancing crop science and improving phenotyping efficiency.

Two types of phenotyping devices : the large phenomobile, and the 'literal' (a light and easy-to-carry system). Credit : Arvalis and Hiphen

Remote sensing for Photosynthesis Crop Improvement and Carbon Sequestration

Advances in remote sensing have enhanced photosynthesis monitoring for crop improvement. Optical, thermal, and microwave sensing at canopy scale provide key agronomic data, including height, leaf area index, albedo, temperature, and soil moisture. Sensor platforms range from proximal (e.g., towers, UAVs) to intermediate (aircraft) and satellite levels. Applications include phenotyping, land-use monitoring, yield forecasting, optimisation, and ecosystem service estimation, such as carbon sequestration. Satellites support precision agriculture by estimating nitrogen deficiency via chlorophyll content and using thermal imaging for irrigation management. Integrating satellite data, local observations, expert insights, and models is critical for robust crop improvement strategies amid climate change.

A Data Platform for Photosynthesis research

Targeting complex and dynamic processes such as photosynthesis in next generation crop breeding will require a highly integrated approach. Data platforms to collect, manage and model direct and indirect photosynthesis data will be an important future resource. The recently established Jan IngenHousz Institute (JII), based in Wageningen (NL), has a mission to address this issue on a global scale to accelerate cohesion at multiple levels. An open science platform is being developed to probe photosynthesis at scale, under field conditions. This will link the development and application of novel, high-throughput sensors, data science, and genetic resources at previously unattainable scales. These tools will be deployed among a community of researchers to link the EU with teams in many international countries, across disciplines, from basic to highly applied science and engineering, to understand the conditions limiting photosynthesis. Through sharing resources and knowledge, rapid progress is expected to realize true gains in productivity.

JII Jan IngenHousz Institute

The potential of computational models to accelerate translation of improved photosynthesis to crops

Modelling provides the possibility to guide the identification of modifications (e.g. gene knock-outs, mix-and-match strategies, protein engineering) that can modify photosynthesis in a desired direction, to pinpoint genes that control photosynthesis-related traits, and to identify genotypes with improved photosynthesis under specific conditions.

Current mechanistic models of photosynthesis often lack accurate species-specific parameterization due to challenges in generating high-quality data, that can increase identifiable parameters and/or reduce variability. Resolving this calls for new measuring technologies to obtain data that facilitate model parameterization. These models hold significant potential to identify breeding targets by: (i) relying on the coupling of mechanistic models with machine / deep learning approaches via (bio)physics-constrained neural networks, (ii) advances in in *silico* design of metabolic engineering strategies, based either on enzyme engineering, mix-and-match strategies, and novel chemistries, and (iii) hybrid models that integrate photosynthesis in larger metabolic and developmental contexts. In addition, developing genotype-specific photosynthesis models will pave the way for identification of condition-specific limitations to photosynthesis, that can be tested with advances in measurement technologies.

To fulfill the potential of photosynthesis models, future projects must prioritise testing model predictions from the outset, embedding a robust model-test-refine cycle throughout their duration. Integrating expertise across scales will benefit from involving multiple modelers in projects. Establishing an Integrative Photosynthesis Modelling Network could coordinate synergistic efforts across projects.

Barriers to translation of research

Photosynthesis improvement strategies in crops offer significant potential to increase or stabilise yields and often reduce inputs. These strategies address multiple societal challenges and policy objectives. But most photosynthesis research remains underutilised by industry. Through stakeholder workshops and surveys, we examined the barriers to industry translation from both researcher and value chain perspectives.

Challenges	Problem	Possible solutions
Historical lack of funding for plant breeding innovation by Europe.	We estimated that less that 0.5% of the Horizon 2020 budget was used for crop improvement.	Inclusion of more photosynthesis and resilience crop related calls in Cluster 6 and FP10.
Inconsistent (3-5 years) funding streams in plant research.	Funding too limited to deliver significant increases in TRLs for crops; disruption of successful consortia slows progress and disrupts pathways to impact.	Conditional longer funding available for successful consortia to develop innovation for successful projects delivering the Key Exploitable Results requested.
Access to germplasm sources	Industry would benefit if public researchers worked on more modern germplasm. Industry would like better access to germplasm collections	Collaboration with industry encouraged in PPP. Funding for better curation and characterisation of germplasm collections for use.
Adoption of photosynthesis as a key trait by breeders.	Survey showed that the benefits of improved photosynthesis were not known by many breeders	Education around what improved photosynthesis can do in crops. More research collaborations encouraged with Industry.
Infrastructure problems for carrying out field trials in public research organisation.	Lab to field is problematic for public researchers due to the limited facilities, and personnel for field trials	Promote collaborations with industry partners. Promote the use of the network of EC Living Labs.
A need for better sensors and phenotyping tools, for field work	Photosynthesis is a complex trait, user friendly devices for breeder/grower communities are needed if promising traits are to be adopted.	Sensor development and AI are key for quickly advancing photosynthesis translation and should be invested in. CAPITALISE is developing field devices.
IP and Industry collaborations	IP and the freedom to operate is a significant issue for breeders to take up research results	More clarity in collaborative agreements between public researchers and industry.
Acceptance of NGT and genetically modified crops and derived products.	The EC funds innovative research using NGTs and genetically modified plants. Uptake by industry is hampered by perceived public opinion.	A need to speed up developing policy for more lenience towards NBTs in Europe. Education around the need for NGTs as solutions to growing societal needs.

LCA assessments

Life Cycle Assessment (LCA) supports sustainability-focused breeding by evaluating how target traits impact the production chain. It aids decision-makers and breeders in anticipating environmental, social, and economic effects, requiring detailed data on inputs, outputs, and scaling effects from small to large processes. LCA aims to guide the development of sustainable crops with enhanced photosynthesis. Under this scenario, there is a challenge to perform a prospective analysis of a low-to-mid TRL, and to scale up to higher TRLs. Field trials must capture real-world environmental and economic data to refine models. Educational tools, including gamification, can engage decision-makers and citizens, illustrating the costs, benefits, and trade-offs of photosynthesis strategies and breeding methods.

The need for societal acceptance

In Europe today crop breeding is primarily based on conventional modern breeding techniques. The acceptance of New Genomic Techniques is important for tackling global challenges such as food security, sustainability, and climate change. NGT derived crops are controversial due to concerns about safety, ethics, and environmental impacts. For these crops to gain broader acceptance, it is crucial to address concerns through clear communication, rigorous regulation, and education on risk.

The CAPITALISE, PhotoBoost, and Gain4Crops projects explored different aspects of photosynthesis research. The social sciences teams focussed on the attitudes of downstream users - consumers, farmers, and the agri-food industry - towards enhanced photosynthesis, using modern breeding techniques, and the potential adoption of more controversial New Breeding Tools (=NGTs). These biotechnology tools enable direct gene editing or in synthetic biology create greater levels of genetic modification to advance crop breeding cycle. Openness to biotechnology and NGTs increased when the drivers were linked to societal challenges, such as improving crop resilience to climate change.

The work across the projects identified the need for engagement with value chain actors and citizens to improve literacy on photosynthesis, and the use of biotechnology in crop breeding to effectively enhance understanding and acceptance of NGTs.

The following recommendations are based on consultations from the three projects:

- **Develop an EU-wide communication strategy in concert with the new policy on NGTs and perceived risks**
- **Ease regulation for sustainability-focussed crop improvement that utilises SDN-1 techniques**
- **Balance research funding between discovery research and applied plant breeding programmes that capture societal needs and maximise sustainability**
- **Involve farmers in early stages of problem identification and in formal field trials and phenotyping.**

This brochure, and a longer version of this Roadmap can be accessed here.

Contributors to the roadmap

The Consortia from 4 photosynthesis projects:

CAPITALISE Workshops: 1&2: The needs of Industry; The barriers to translating academic research to crop breeders:

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Workshop 3 Translational Photosynthesis, co organised by CAPITALISE and the French Groupment de Recherche, involved the 4 photosynthesis projects and invited experts.

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